CASTING OF Al-GRAPHITE METAL MATRIX COMPOSITE STRIPS USING SINGLE ROLL CONTINUOUS STRIP CASTER

by

Shyam Deo Pal

DEPARTMENT OF MATERIALS AND METALLURGICAL ENGINEERING

Indian Institute of Technology Kanpur

OCTOBER, 2002

CASTING OF Al-GRAPHITE METAL MATRIX COMPOSITE STRIPS USING SINGLE ROLL CONTINUOUS STRIP CASTER

A thesis submitted
In partial fulfillment of the requirements
For the degree of

Master of Technology

By
SHYAM DEO PAL

To the

DEPARTMENT OF MATERIALS AND METALLURGICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

October 2002

CERTIFICATE

It is certified that the work contained in this thesis entitled "*Casting of Al- Graphite Metal Matrix Composite strips using Single Roll Continuous Strip Caster*", by ***Shyam deo Pal***, has been carried out under my supervision and that this work has not been submitted elsewhere for a degree

October 2002

Dr S P Mehrotra
Professor,
Department of Materials and Metallurgical Engineering, IIT Kanpur

8/10/02
Dr S C Koria
Thesis Coordinator

ACKNOWLEDGEMENTS

I owe my debt of sincere thankfulness to my guide Dr S P Mehrotra, for giving me an opportunity to work on this project He made me understand the exact formulation of the problem, and the clear-cut objective of all the work that I performed in this project During that period, his inspiring and expert guidance has helped me a lot to successfully complete my project I must mention that it was his supporting and encouraging attitude to let me explore new facts and techniques by doing experiments on my own, which not only helped me in learning but also added new dimensions to my work

I am also very much thankful to Mr K S Tripathi who has helped me during all my experimental works

I cannot forget the time that I had spend staying at IIT Kanpur with my friends and batchmates of my graduating college B I T Sindri, namely, Amitav Shankar, Gyanda Saran, Amit Kumar, Rajesh sharma and S K Rout who has given me much needed help and support There company has left unforgettable memories in my mind which I will cherish whole of my life

I am grateful to my parents and family members who has supported and given me invaluable love and affection during my tough times

Shyam deo pal

CONTENTS

ABSTRACT

Aluminium metal matrix composites in strip/sheet form have applications in automobiles and aerospace industries The demand for these materials has been growing at a fast pace from several decades It is therefore desirable that these materials are produced at a lower production cost and in large quantities This present investigation deals with preparing Aluminium - Graphite MMC strips directly from the composite melt prepared by vortex method in combination with new technique of single roll continuous strip caster developed by Mehrotra and coworkers[1]

This investigation was two pronged In the first stage, the composite melt was prepared by the vortex method and strips were produced with the strip caster machine simultaneously optimizing the process parameters of casting In all casting experiments stirring was done at 400 rpm as it was found to be the optimum stirring speed, which resulted in better wettability of graphite particles and reduced entrapment of gases in the casted strip Strips were also produced with different amount of graphite inoculated in the melt, varying graphite particle size and with different operating parameters of the casting, viz speed of rotation of the caster drum, and the temperature of the melt

The second part of this investigation involved evaluation of microstructure and properties of these strips in as cast and heat-treated conditions Mechanical properties, which are of major concern, included tensile strength, yield strength, percentage elongation, hardness and wear properties (as graphite is a good solid lubricant) Tensile strength was measured by preparing the tensile specimen of ASTM standards in longitudinal direction While the tension tests were done on INSTRON 1195 tension testing machine, the hardness measurement were carried out on automatic Rockwell hardness tester on R_B scale Micro structural aspects of the investigation essentially involved observing the strips under optical and scanning electron microscopes to see the distribution of the graphite particles and the internal quality of the strips SEM examination was done on JOEL JSM 840 machine at

various magnifications to observe reinforcing particles, pores and inclusions at various locations of the sample

Investigations showed that the recovery of the graphite particles in the composite increase from 20% to 60% by the addition of 2 5 wt % of magnesium Tensile strength and yield strength of the strips also increase with magnesium addition though at the expense of percent elongation Heat treatment of the strips in an inert atmosphere resulted in increased strength manifolds while ductility improved remarkably by subsequent aging at elevated temperature Composites with smaller size graphite particles had higher strength than the composites with coarser size graphite particles Mechanical properties of cast composite strips improved with increase in speed of the rotation of the caster drum, which also resulted in thinner strips In all casting experiments stirring was done at 400 rpm as it was found to be the optimum stirring speed, which resulted in better wettability of graphite particles and reduced entrapment of gases in the casted strip

List of Figures

List of Tables

CHAPTER 1.

INTRODUCTION

Composite material can be defined, in a general way, as a man made engineered combination of two or more materials, where tailored properties are achieved by systematic combinations of different constituents In technical terms it is defined as a material consisting of two or more physically and or chemically suitably arranged faces with a separating interface whose characteristics are not depicted by any of the components in isolation

The classification of composite materials may be done based on various factors, such as nature of the matrix, type, size and nature of the reinforcement, etc On the basis of the nature of the matrix these are classified as

1 Polymer matrix composites (PMCs)
2 Metal matrix composites (MMCs)
3 Ceramic matrix composites (CMCs)
4 Intermetallic matrix composites (IMCs)
5 Elastomer/Rubber matrix composites (RMCs)

On the basis of size and kind of reinforced material they are classified and sub classified as

1 Continuous fiber composites
    - Single layered
    - Multi layered
2 Discontinuous fiber composites
    - Particulate
    - Platelets
    - Whiskers

Since this thesis mainly concerns with the metal matrix composites with discontinuous particulates, only these are discussed in what follows

1.1 METAL MATRIX COMPOSITES (MMCs)

As the name suggests, MMC is the engineered combination of a metal as a matrix and some reinforcing object in the matrix Conventional material in monolithic form has several limitations in terms of achievable combination of strength, stiffness, coefficient of expansion and density so engineered MMC consisting of continuous or discontinuous fiber, whiskers or particles in a metal results in combination of very high specific strength and specific modulus

1 2 FABRICATING METHODS OF MMCs

Various fabricating methods of MMCs can be classified into the following two based categories and sub categories

1 Solid phase fabrication methods
   a) Diffusion bonding
   b) Powder metallurgy (P/M) route
2 Liquid phase fabricating methods
   a) Liquid metal infiltration
   b) Squeeze casting
   c) Spray co deposition
   d) Compocasting

In the first category, the P/M route is the most successful and commonly used technique In the second category, liquid metal infiltration, squeeze casting and compocasting methods, generally referred to as the casting route methods, are more commonly used techniques There are several advantages of the liquid phase methods over the solid phase methods, which make them more popular and commercially viable Major advantages are

a) Complex shapes can be produced easily
b) Shorter fabrication times
c) Lesser cost of unit production
d) Secondary processes of fabrication are minimized or even completely eliminated at times

In the present investigation, aluminium graphite MMC is cast in a strip form The composite being prepared using the vortex liquid dispersion method, is chosen primarily for its low cost and ease of operation

1 3 INDUSTRIAL METHODS TO PRODUCE MMC STRIPS

At present in industry, following methods are utilized to produce MMC strips

- Lamination
- Deposition
- Spray forming method
- P/M route
- Continuous casting methods

Generally casting of MMC in strip or sheet form is performed in several steps in series

- Casting of ingots or billets from the liquid composite melt
- Subsequent rolling of the ingot or billet to produce strips/sheets
- Intermediate heat treatment of the product formed
- Various finishing operations applied to produce final finished product in desired shape and size

Out of these various steps, the rolling step is the most crucial one since it results in a high rejection rate of the strip/sheets due to cracking This happens because composite in general are more brittle than the metal constituting the matrix of the MMC This high rejection rate makes the overall rolling operation quite expensive and energy extensive Because of these problems associated with the rolling of composites, efforts are going on for several years to develop techniques similar to continuous casting of metal strip/sheets

Some of these techniques, which show potential for commercial applications, includes

- Chill block melt spinning
- Twin roll casting
- Melt drag processes

Among the melt drag processes, the Single Roll Continuous Strip Caster process is one of the newly developed techniques to produce near net shape continuous strip In this thesis this technique has been adapted to produce aluminium graphite MMC strips The technique is essentially used to produce MMC strip directly from the melt thereby saving energy and skipping several intermediate unit operations that are needed in the conventional method of strip/sheet production

1 4 USES OF MMCs

MMCs have remarkable properties and promising applications and use in automobiles, aerospace industry, sport and house hold items MMC in general and aluminium graphite MMC in particular have the following applications and properties

- Making of cylinder pistons and other engine parts – Cast aluminium graphite alloy piston, used in single cylinder diesel engine with a cast iron bore, reduces fuel consumption and frictional horsepower losses [2,3] Also because of the lower density of these composites the overall weight of internal combustion engine is reduced Due to their good antiseizure properties, engines made of these composite do not seize during cold start or failure of lubricant
- Heavy machinery parts and equipment of aerospace structures – To avoid vibrations in aerospace structure these composites due to their good damping capacity are used to make parts and components, which can replace cast iron Window frames of aerospace structures and shock absorbing cylinders, which are made up of the sheets of these composites Are the typical products which utilize damping property of these materials
- Sliding electrical contact components – In electrical contact equipments sometimes sliding contact is needed for continuous electric supply in moving parts Thus, to have a better electrical contact, as well as, good lubrication between moving parts these composites are successfully used
- Sports goods – Tennis rackets, golf sticks, mountain bike frames etc are made of such composites where their lightweight and good strength properties, are made use of

1.5 OBJECTIVE AND PLAN OF THE PRESENT INVESTIGATION

Observing the growing demand of MMC in strip form, methods have to be developed to produce MMC at cheaper cost and on large scale on continuous basis to save energy and production time. Since aluminium graphite composite in sheet form is also having similar demand and applications, a composite made up of binary alloy of aluminium and silicon as metal matrix and particulate graphite incorporated in the matrix as reinforcing material is produced. The present investigation has the main objective of establishing the feasibility of producing these composites in strip form using the single roll continuous strip caster machine and evaluate the properties of these steps to decide whether these can be used in the industry on regular basis.

The plan of work in the present investigation can be divided into two parts. In the first part composite strips are produced on the single roll strip caster under various operating conditions. Optimum conditions for producing quality composite strips are established after performing several experiments. In the second part, evaluation of properties of the strips thus produced is done by analyzing the microstructure and measuring mechanical properties of the strips. Micro structural evaluation involves the examination of segregation of graphite particles, porosity and inclusions, etc. through SEM and optical microscopy. Mechanical properties evaluation involves hardness measurement and tensile testing of strips determining the percentage elongation and yield stress of the strips. These measurements have been carried out on both as-cast and heat-treated composite strips. Addition of small amount of magnesium makes this composite heat treatable and the strength improves with treatment.

This thesis has six chapters. The first chapter is a brief introduction and the second chapter presents the background literature. The single roll continuous strip caster, which has been used for casting MMC strips, is described in chapter 3, and experimental procedures are presented in chapter 4. Results obtained in this investigation are presented and discussed in chapter 5, while chapter 6 gives the summary and conclusions.

CHAPTER 2.

BACKGROUND LITERATURE

In this chapter a brief description of various methods of producing MMCs is presented Special emphasis is given to produce MMC strips by different techniques, which are presently being used in industries Since this investigation deals with a liquid phase fabrication technique of fabricating MMC strips, various aspects related to mixing of particles in the melt, solidification of the melt and the interfacial interaction of reinforcing particles with the matrix are described at the end of this chapter

2 1 FABRICATION TECHNIQUES OF MMCs

There are several fabrication techniques available to manufacture the MMC materials These can be broadly classified into two categories

- Solid phase fabrication methods
- Liquid phase fabrication methods

These two routes involve widely different techniques of producing MMCs having certain merits and demerits

2 1 1 Solid phase fabrication methods

These methods include the following

2 1 1 1 Diffusion bonding

This method is normally used to manufacture fiber reinforced MMC with sheets or foils of matrix material Figure 2 1 shows the steps involved in fabricating MMC by diffusion bonding Here the matrix metal or alloy, in the form of sheets and the reinforcement material in the form of fiber are chemically surface treated for effectiveness of interdiffusion Fibers are then placed on the metal foil in predetermined orientation and bonding takes place by press forming directly Diffusion bonding in vacuum conditions is more effective than in atmospheric conditions Because of the relatively low temperature involved, a fiber coating

treatment for solid phase fabrication is not as critical as in the case of liquid metal infiltration, but the pressure applied for enhancing diffusion bonding may cause damage The applied pressure and temperature as well as the duration of diffusion bonding to develop, vary with the composite systems

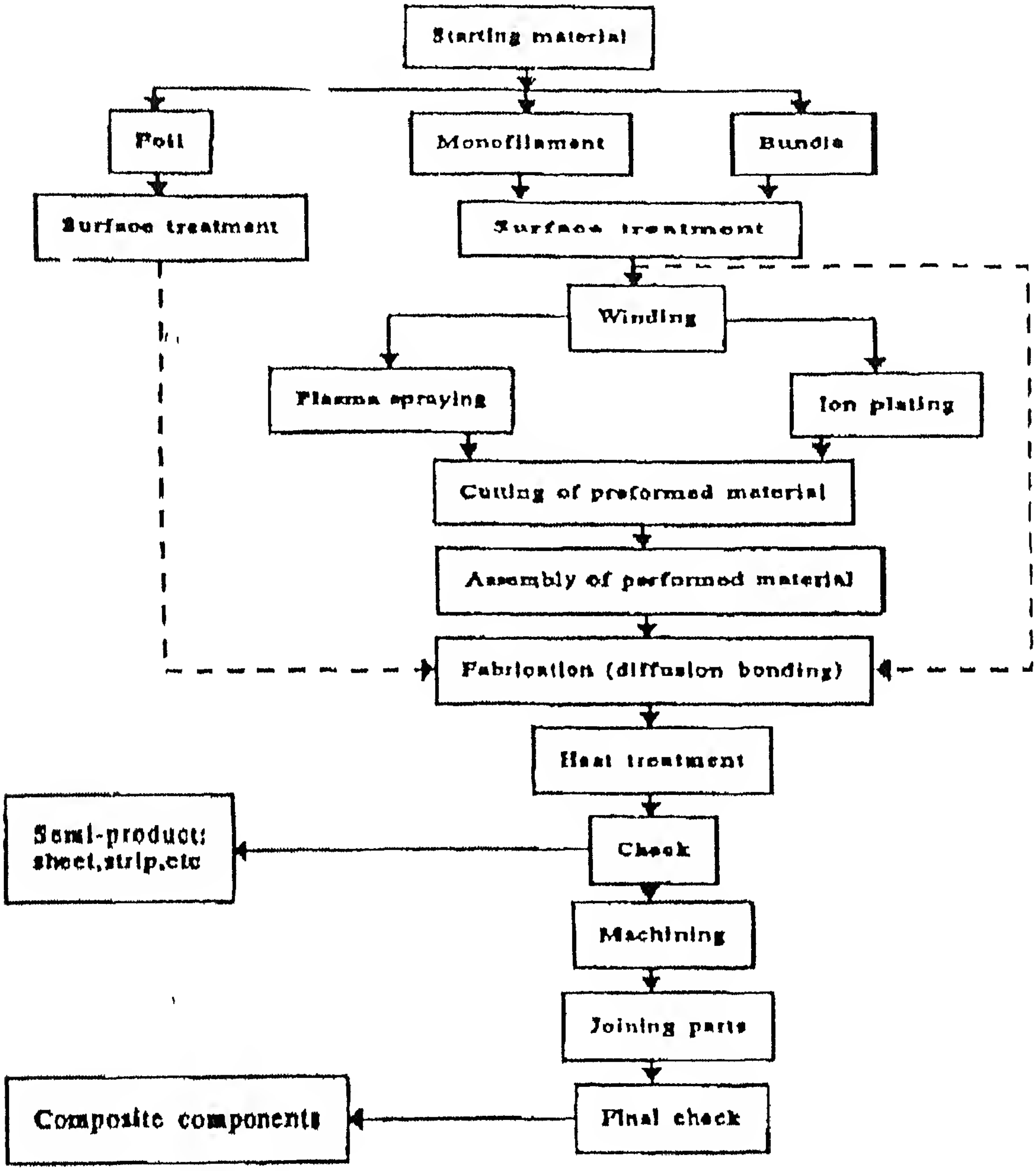


Fig 2 1 Flow chart for composite fabrication by diffusion bonding

2.1 1.2 Powder metallurgy technique

This is one of the most commonly used methods for the preparation of discontinuous reinforced MMCs Figure 2 2 shows the flow chart of the general powder metallurgy route to fabricate these composites In this process powders of matrix materials and reinforcements are first blended and fed into a mould of the desired shape

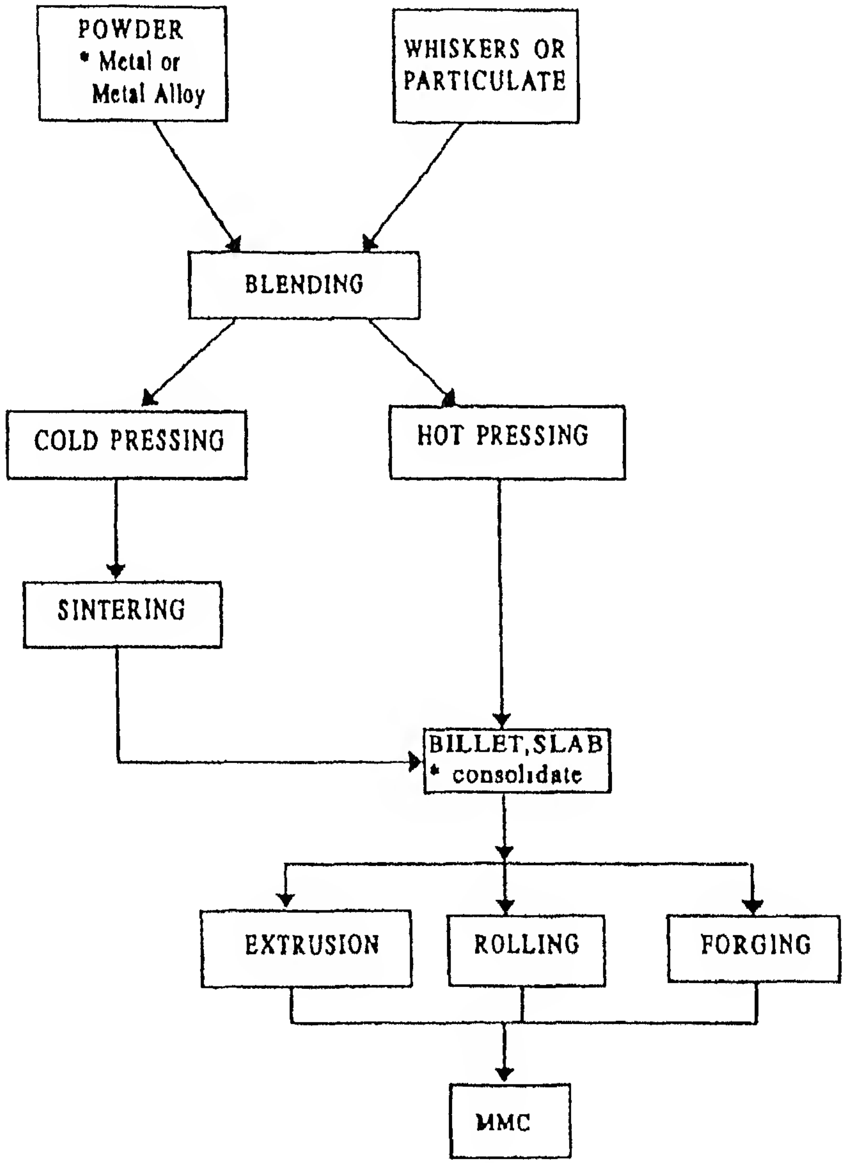


Fig 2 2 Flow chart for composite fabrication by powder metallurgy

Pressure is then applied to further compact the powder (cold pressing) In order to facilitate the bonding among the powder particles, the compact is then heated to a temperature, which is below the melting point but high enough to develop significant solid state diffusion (sintering) The consolidated product is then used as a MMC material after some secondary operation like extrusion to increase the mechanical strength Metallic materials such as copper aluminium, cobalt, titanium, molybdenum based alloys and steel are often used in the powder process as matrix material with reinforcing particulate being SiC/graphite/Ni/Ti or Mo This technique offers several advantages over fusion metallurgy of diffusion bonding Some of these are

- Lower temperature can be used during operation which helps in minimizing undesirable interfacial reactions which occurs at high temperature between matrix and the particulates
- In some cases it helps to prepare composites that cannot be prepared by fusion metallurgy like SiC particles addition in molten Ti – alloy
- A wider range of reinforcement levels of the particulate can be used as compared to those in the liquid melt

2.1.2 Liquid phase fabrication methods

This fabrication route, also called as the casting route, includes of the following techniques

2 1 2 1 Liquid metal infiltration

This process is also called fiber tow infiltration Fiber tow can be infiltrated by passing through a bath of molten metal Usually the fibers must be coated in line to promote wetting Once the infiltrated wires are produced, they must be assembled into a preform and given a secondary consolidation process to produce a component Secondary consolidation is generally accomplished through diffusion bonding or hot moulding in the two-phase liquid-solid region The fabrication process of MMC by vacuum metal infiltration is shown in Fig 2 3 The application of this process is limited because of the wetability problem of reinforcement with almost all liquid metals and the degradation of most fibers at high temperature The surface tension

forces and degree of wetting under the infiltration conditions mostly determine the extent of penetration and bonding between the reinforcements and the matrix The infiltration process can be done under atmospheric pressure, inert gas environment and in vacuum .

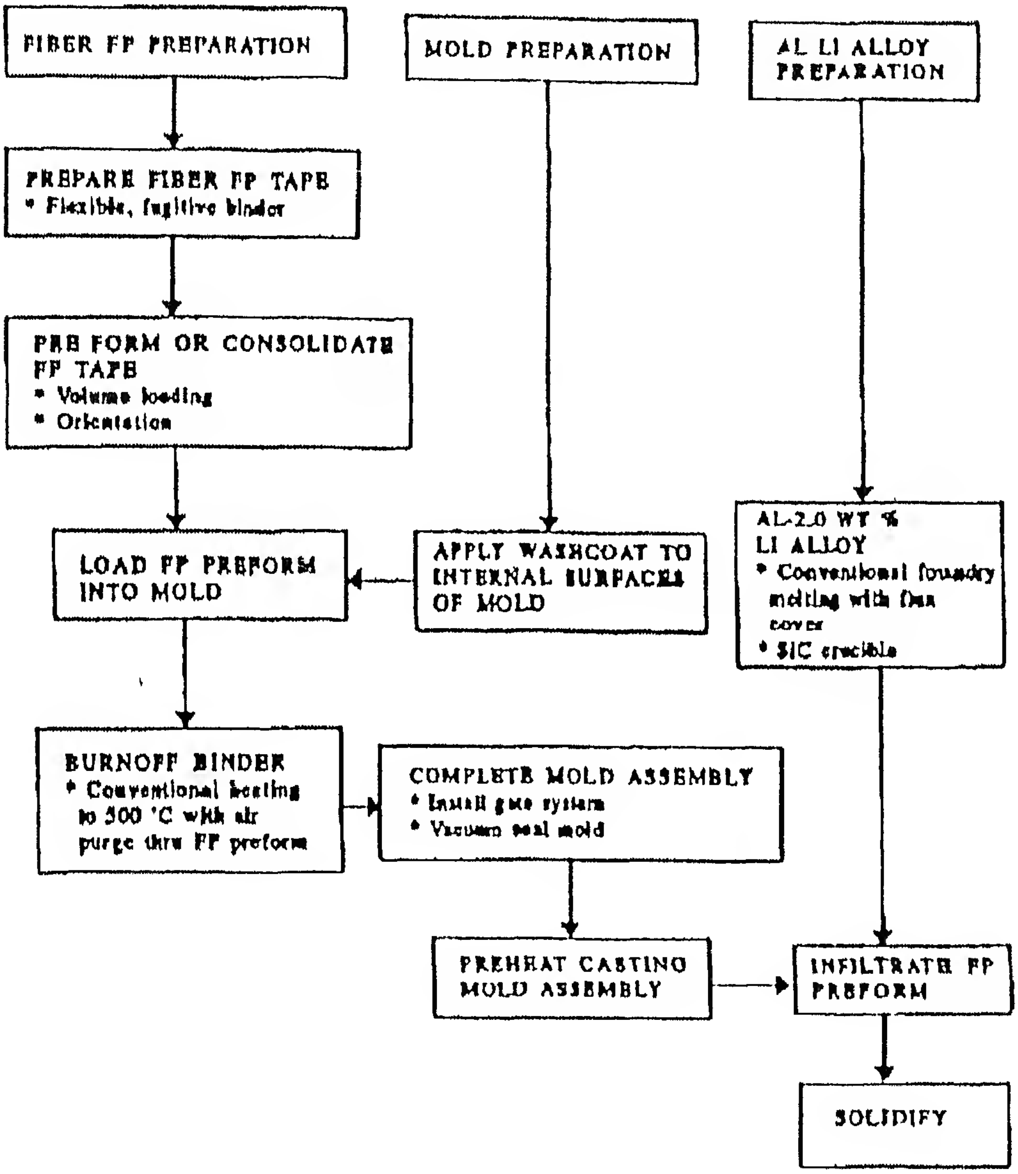


Fig 2 3 Flow chart for FP/Al plate castings

Among these, vacuum infiltration is the best way to fabricate MMCs because in vacuum the surface activity of fibers is higher and thus better wettability can be achieved Metal matrix composites of the type Al_2O_3 whiskers reinforced Al, Gr/Al,

B/Mg and C/Mg have been fabricated by this technique The fiber FP/aluminium casting infiltration process differs from the liquid infiltration process used for preparing graphite/aluminium composites because the FP/metal fabrication process permits casting of complete parts in a single infiltration step

2 1 2 2 Squeeze casting

It is defined as the ability to forcibly charge liquid metal into a preheated ceramic fiber or any reinforcement preform which is set in a metal die and thus to alloy the liquid metal to solidify by applying a high pressure thereby squeezing the liquid metal This fabrication process is shown in Fig 2 4 The preform of the ceramic fiber is pre-heated to several hundred degrees centigrade below the melting temperature of the matrix and then set into a metal die Al or Mg alloy is heated to just its melting temperature and is squeezed into the fiber preform by a hydraulic press to form the mixture of fiber and molten metal Figure 2 5 shows a preforming method by pressing This process is solely employed for the benefits of high productivity and easy formability The composites produced by this method are of good quality and have high reliable strength This has the major advantage that, since the solidification time is small and high pressure (70 – 100 MPa) is applied to squeeze the liquid metal, there is no reaction zone development on the interface of matrix and reinforcement, which gives a void free and high strength composite It is generally applicable to fabricate composites like Al_2O_3/Al, C/Mg, SiC_w/Al, Si_3N_{4w}/Al This process has the major limitation of size of the parts that may be cast because of the high-pressure requirements

2 1 2 3 Spray Co-deposition

This is an economical method of producing the particulate composite using the spray deposition method A schematic diagram of the process is shown in Fig 2 6 The alloy to be sprayed is melted by induction heating in a crucible The crucible is pressurized and the metal is ejected through a nozzle into an atomizer where at the same time particles (reinforcements) are injected into the atomized metal

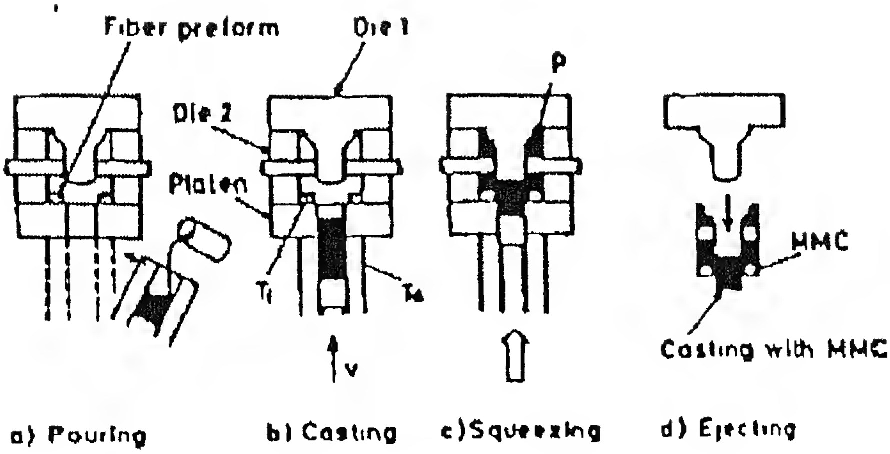


Fig 2.4 Sequence of a squeeze casting machine

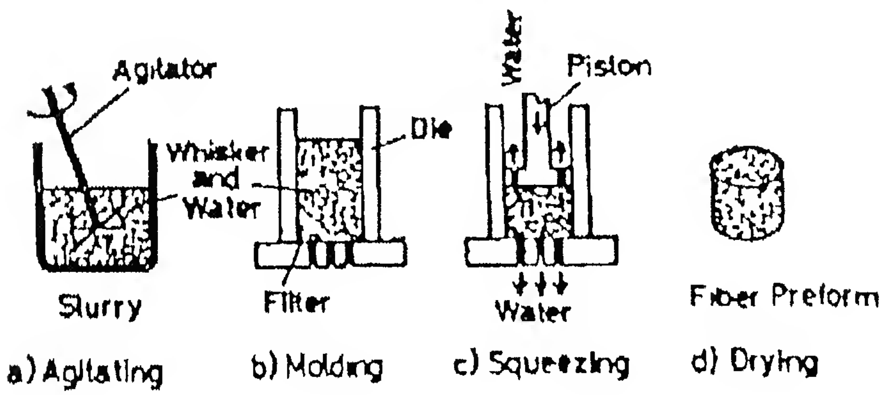


Fig 2 5 Fabrication process of a fiber preform by press-forming

and deposited on a preheated substrate placed in the line of flight A solid deposit is build up on the collector The deposited strip when cold is moved from the substrate for the subsequent rolling The shape of the final product depends on the atomizing condition and the shape and the motion of the collector Various second phase particles namely sand, alumina, SiC, chilled iron, graphite etc can be successfully incorporated in aluminum and Al-5Si alloy matrixes This route can be used for the production of large quantities of high quality MMCs both in technological and economical sense It is used to produce materials, which have applications including friction materials, electrical brushes and contacts and cutting or grinding tools Full density is not achieved during this process and hot or cold rolling is used to densify the material prior to mechanical testing

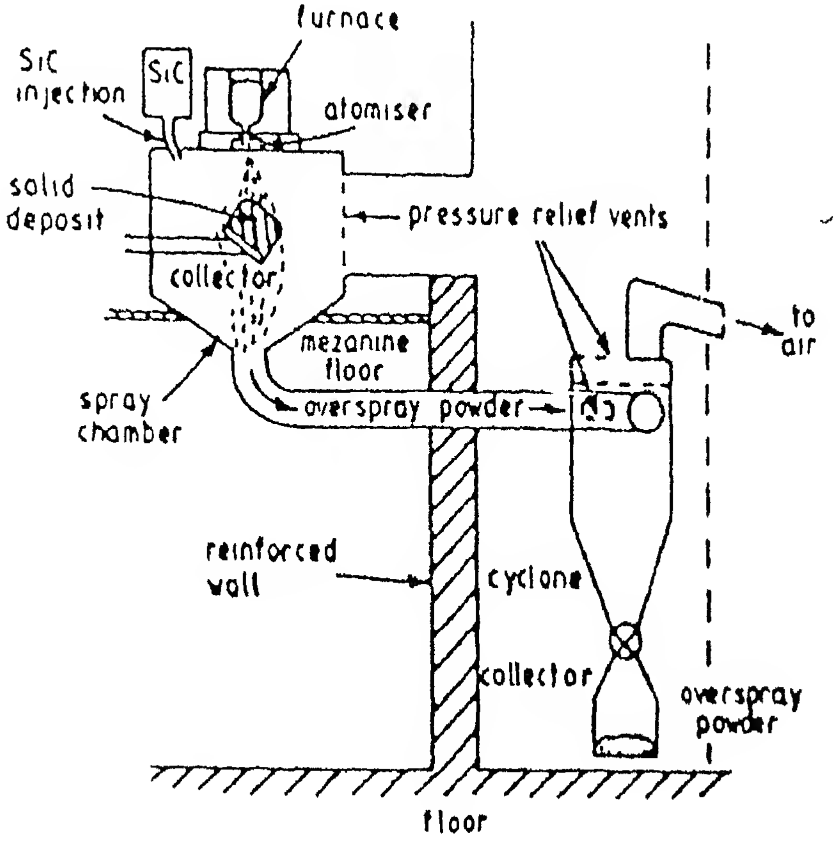


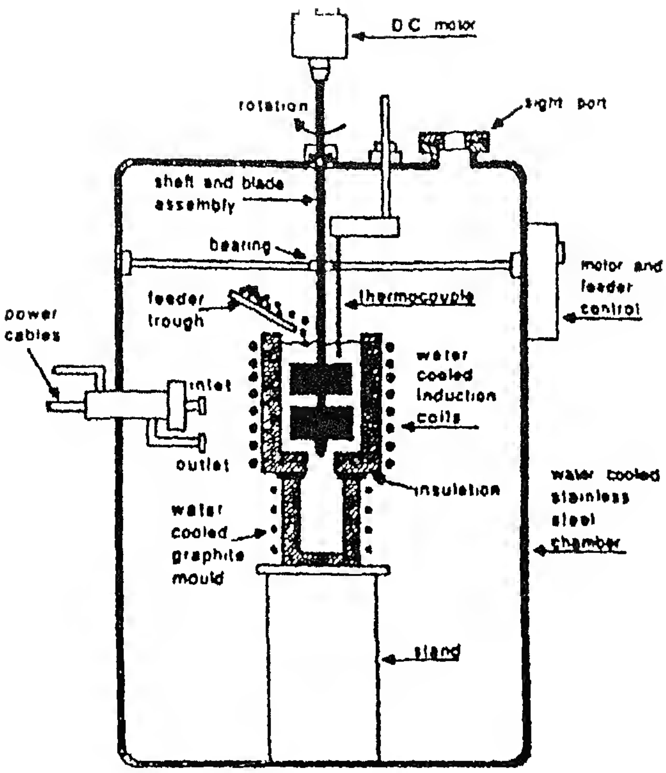
Fig 2 6 Schematic diagram of spray deposition equipment

2.1.2.4 Compocasting

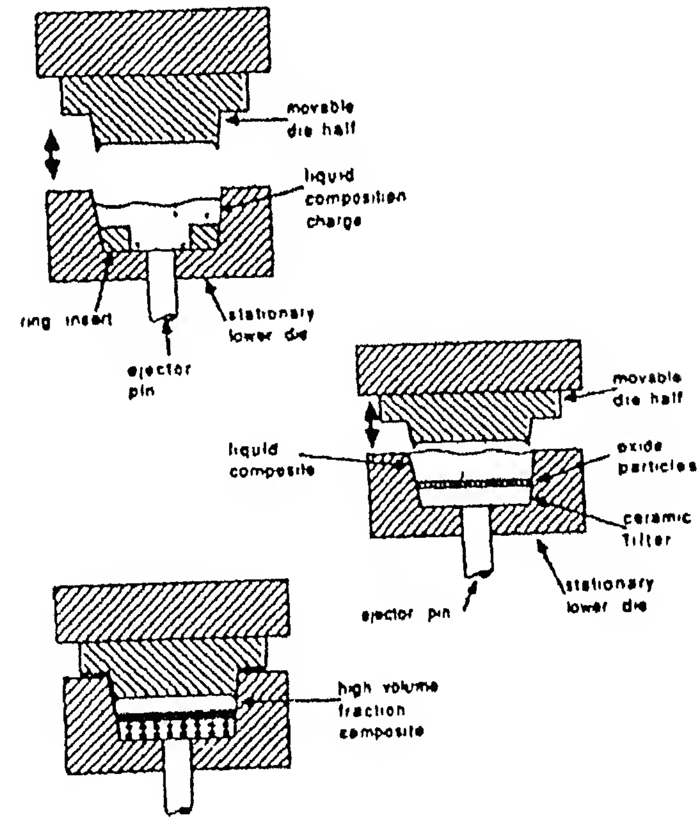
This process is an improved version of slush or stir casting, also known as semisolid casting or rheocasting. A schematic diagram of this process is shown in Fig 2.7. In this process, first metal alloy is placed in the system with a blade assembly in place. The chamber is evacuated and the alloy is then superheated above its melting temperature and the stirring is initiated by a DC motor to homogenize the temperature. The induction power is gradually lowered until the alloy is 40 to 50% solid, at which point the non-metallic particles are added to the slurry. The temperature is raised while adding reinforcement but ensuring that the total amount of solid, which consists of fibers and solid globules of the slurry, does not exceed 50%. Stirring is continued until interface interaction between the particulates and the matrix promote wetting. The melt is then superheated to above its liquidus temperature and bottom poured into the graphite mould by raising the blade assembly. Since the dispersoids are entrapped between the primary solid phases in the slurry, they are prevented from floating, settling or agglomeration. The increased mixing time at lower temperature after additions help in promoting wetting and improved bond formation. This process has the advantages that it can be performed at temperature lower than the those which are conventionally used in foundry practice during pouring, resulting in reduced thermo chemical degradation of the reinforcement surface. But it also has a demerit that the residual pores between fibers cannot be eliminated completely and entrapment of gases causes surface blisters in the castings while making the ingots.

2.1.3 Comparison of different techniques

To summarize the various techniques of fabricating MMCs, Table 2.1 compares these techniques with respect to their cost, applications and different conditions of fabrication.



(a)



(b)

Fig 2 7 Compocasting (a) mixing of fibers (or particulates) with metal followed by (b) die casting

Route	Cost	Application	Comments
diffusion bonding	high	used to make sheets blade, vane shaft structural component	handles foils or sheets of matrix and filaments of reinforcing element
powder metallurgy technique	medium	maily used to produce small objects (especilly round) bolts pistons valves the high strength and high-resistant materials	both matrix and reinforcement are used in powder form, best for using particulate reinforcement Since no melting is involved, there is no reaction zone developed, showing high strength comp
liquid metal infiltration	low-medium	used to produce structural shapes, such as rods, tubes, beams with maximum properties in a uniaxial direction	filaments of reinforcement are used
squeeze casting	medium	widely used in automotive industry for producing different components such as piston, connecting rod rocker arm, cylinder head, suitable for making complex objects	generally applicable to any type of reinforcement and may be used for large-scale manufacturing
spray co-deposition	medium	used to produce friction materials electrical brushes and contacts cutting and grinding tools	particulate reinforcement is used Full density materials can be produced
compo-casting	low	it is widely used in automotive, aerospace, industrial equipment and sporting good industries used to manufacture bearing materials	suitable for discontinuous fibres especially particulate reinforcement

Table 2 1 Comparison of different techniques

2 2 PRESENT TECHNIQUES TO PRODUCE MMC STRIP/SHEETS

Following methods are commonly used to produce MMC strips and sheets

- Lamination
- Deposition
- Spray forming methods
- Powder metallurgy route
- Continuous strip casting methods

2 2 1 Lamination

This is a group of methods in which strips are produced by laminating the components of the composite in alternate layers [4] Temperature and pressure are applied to produce bonding at interface Surface preparation, pressure and time, chemical reaction between the component materials greatly influence the behavior of the strips so produced

2.2 2 Deposition

It involves atomic or molecular scale transport of the component materials Chemical vapour deposition, electroplating, etc are the processes of this type These processes are slow and expensive [5], though the product generally is of high quality

2 2 3 Spray forming method

In this method the matrix in the liquid form is sprayed onto the substrate Here a gun is used in which a flame melts the matrix metal and also propels it in finely divided form towards the substrate Here discrete interfaces do not exist between the metal and the reinforcement as in the case of bonded laminates

2 2 4 Powder metallurgy method

In this method, the matrix metal is in the form of finely divided powder form It is then compacted and consolidated using processes such as sintering, rolling, etc This method can be further subdivided in following two types

- Roll compaction - In this process, first a green strip of metal powders is produced using a binder and plasticizers The strip is then passed through the rolling mill to obtain a coherent strip
- Isostatic pressing – External pressure from equal side is applied to the powdered mass in this process In hot isostatic pressing (HIP), the powder is heated while being subjected to external pressure The pressure source may be hydraulic or may be applied using gas

2 2 5 Continuous strip casting methods

MMC production has the shortcoming of high cost and complex processing technique This is the greatest barrier for it to be utilized on commercial scale Continuous strip casting methods is a step forward to decrease the overall cost of production, simultaneously achieving better properties and shorter production time Following are some of the new techniques of producing continuously cast metal strips [6-9]

1 Chill block melt spinning (CBMS) - It involves formation of a molten jet, which then gets impinged on a rotating drum A typical ribbon width of 3mm and ribbon thickness of 20-200 μm depending upon substrate velocity can be cast
2 Twin roll continuous casting - This process was developed commercially by hunter in 1950's Liquid metal stream impinges between two fast moving rolls in opposite direction and solid strip forms directly from molten metal Strips of gauge thickness of 6 to 10 mm have been cast by this technique
3 Melt drag process- In this process metal is applied to the rotating drum through a nozzle, which gets removed by contact of meniscus with the rotating drum Strips of width up to 300 mm have been produced by this method Here thickness of strips depends upon the metal flow rate, melt temperature and speed of rotation of the caster drum

Schematic diagrams of various continuous strip casting techniques are shown in Fig 2 8

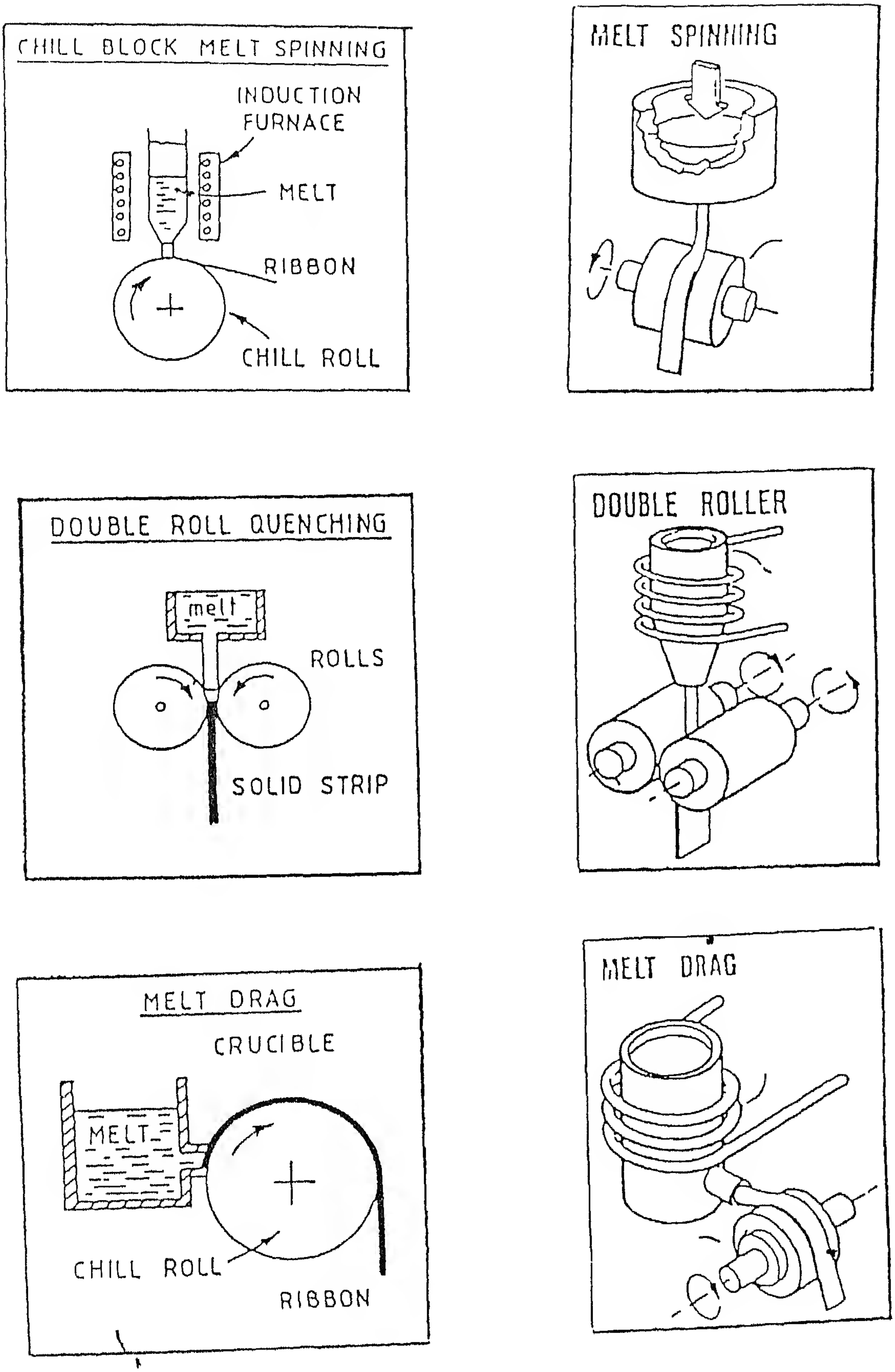


Fig 2 8 Schematic diagram of various continuous strip casting techniques

2.3 MIXING PHENOMENON OF PARTICLES IN MELT

To produce excellent quality MMC strips it is utmost important that the particles added in the melt are properly mixed and uniformly distributed in the melt There are many parameters, which govern this mixing characteristic These are described in some detail below

2 3 1 Wetting characteristics of particles

Wetting is one of the major properties of particle reinforcement in MMC This not only determines the amount of particles that actually get incorporated but also determines the properties of the cast MMC The wetting property or wettability of liquid on a solid surface is indicated by the contact angle θ as described in appendix A1 For wetting to occur contact angle must be less than 90^0

There are various factors that govern the wetting characteristics of a solid particle in liquid melt They are as follows

2 3 1 1 Factors affecting wettability

- Surface tension
- Adsorbsion
- Work of adhesion
- Presence of oxygen
- Surface characteristics of reinforcement

Surface tension – High surface tension i e (γlg) implies larger contact angle, so in order to wet a solid surface by liquid sufficient chemical reaction must take place at the interface between particle and liquid metal so that γsl decreases the contact angle Dalannay et al [10] have shown that a liquid wets a solid surface only if the energy of the bonds that are created across the interface exceeds the surface tension of the liquid

Adsorbsion – It is a physical phenomenon, which takes place between the liquid matrix atoms and the solid particles Reaction between matrix and particles increases the wetting but there is a loss of particles after the reaction

Work of adhesion – It is a measure of the strength of binding between two phases It should be equal to or greater than the surface tension to have the wetting The effect is more pronounced for metals having higher affinity for oxygen [11]

Presence of oxygen – Presence of oxygen causes the formation of oxide layer on the surface of a liquid metal, which has higher affinity for oxygen (like aluminium) This hinders the direct contact between the metal and reinforcement and reduces the bonding strength thereby decreasing the wetting property

Surface characteristics of particles – Nature of the surface of reinforcing particles also affects wetting If particles are contaminated prior to the addition in the melt, wetting is affected by varying degree The contaminants change the surface energy, which further adversely affects the contact angle reducing the wetting

2 3 1 2 Approaches to improve wettability

Various methods have been employed to enhance wetting behavior These include

- Coating of particles
- Addition of alloying element
- Stirring of melt
- Preheating of particles
- Temperature of melt and stirring

Coating of particles – When there is mutual solubility or formation of intermettalic compound then wettability is highest [12] Several elements like copper, nickel, silver, etc have been used for coating of particles [13] Formation

of intermetallic compound changes the interfacial energy by decreasing the contact angle, thereby increasing the wettability Pai [11] has successfully produced graphite particles of size 2-200 μm coated with copper thickness of 2-5 μm These copper coated graphite particles have then been utilized to produce aluminium – graphite particle composite by Surrapa and Rohatgi [14]

Addition of alloying element – Elements which have higher affinity for oxygen than the matrix element, lower the interfacial energy of liquid metals with oxides and enhance wetting property Some of the common alloying elements used for this purpose are magnesium, silicon and lithium

Stirring of melt – Stirring of melt during and after addition of the reinforcing particles improves wettability of particles by the melt Impeller rotational speed as well as the correct blade angle help in good mixing of particles by deflagmating the coagulated particles

Preheating of particles – One of the major causes of poor wettability of particles is the presence of adsorbed gases and volatile compound on the surface of particles, which restrict the direct contact between particles and the melt As in case of aluminium-alloy graphite composites, preheating of graphite particles helps in removing these gases [15] Figure2 9 shows that it is possible to remove most of the volatile substance and adsorbed gases on the graphite particles by heating the particles to 400^0C for about 30 min Figure 2 10 shows that the time required to remove all the volatile substance and gases can be less than 30 min, if the preheating temperature exceeds 400^0C However severe oxidation of graphite particles is noticed at higher activation temperature

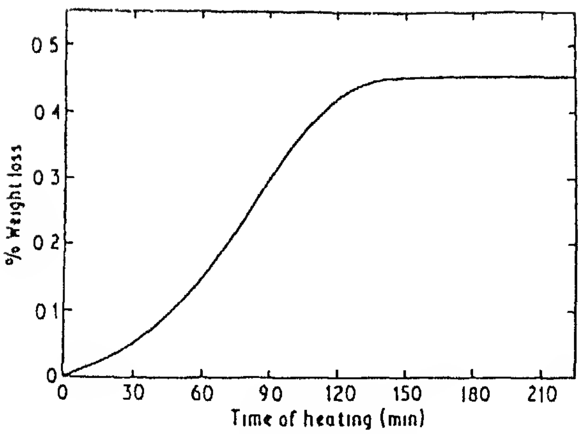


Fig 2 9 Isothermal heating of graphite powder in CO_2 at 400^0C

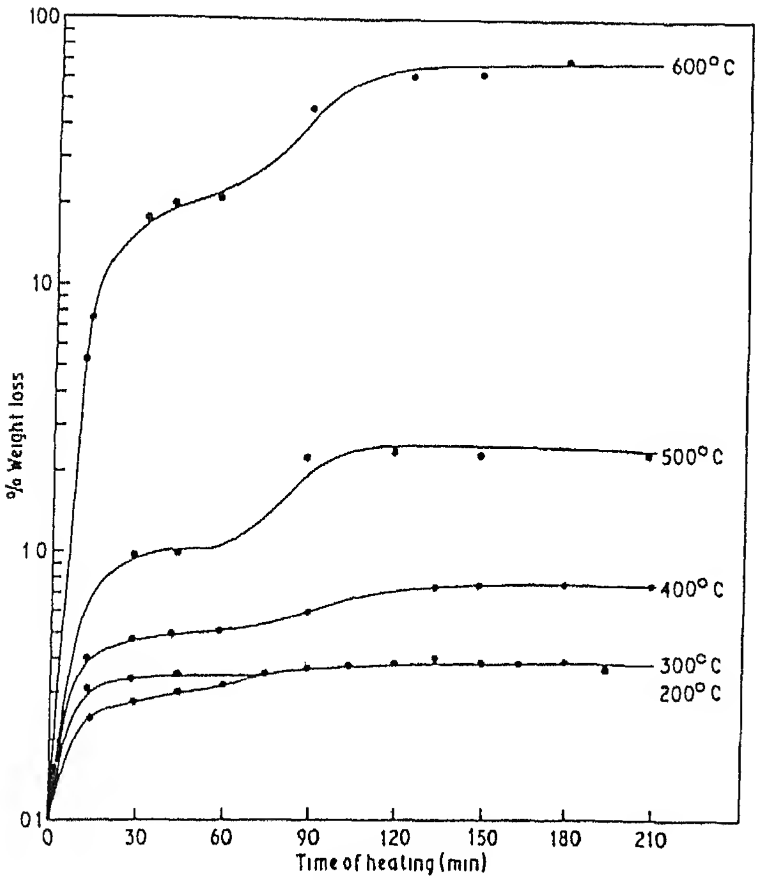


Fig 2 10 Isothermal heating of graphite powder in air at different temperature

Temperature of melt and stirring – High temperature and long time of contact of melt and particle also influence the wetting property Optimized value of these parameters helps in diffusion of carbon through Al_2O_3 layer at high temperature and long contact time, which improves the bonding between the particles and melt in aluminium - graphite system [16]

2 3 2 Particles recovery and particles distribution

Various investigations are reported in literature on particles recovery and their distribution in the melt It is noted that it is very difficult to obtain uniformly mixed melt Some of the inbuilt characteristics of material and melt responsible for this are

- Aggregation and skeleton formation during entry of particles in the melt
- Setting or flocculation of individual particles and particles aggregates in the melt before and during solidification owing to density difference
- Localized pushing of particles by solidifying interfaces causes micro inhomogeneity in particle distribution

Apart from these inherent natural tendencies of materials, there are a few external factors also, which contribute to mixing behavior of particles

1 **Particle size and shape** – Fine particles have the tendency to agglomerate, which prevents good mixing of particles into the matrix So size distribution must be optimized

2 **Percentage of particles** – It has been observed that viscosity is a function of reinforcement volume fraction and size An increase in volume fraction or a decrease in size increases the viscosity of slurry This limits the practically achievable amount of reinforcement to about 30 volume % Since fluidity of Al-Si alloy is higher than pure Al [17], it helps in incorporating more graphite particles in the melt

3 **Rate of addition of particles** – It effects the mixing of particles because high rate of particle addition does not give ample time for perfect mixing and causes particles to float on the surface of the melt and agglomerate This results in poor recovery The optimum rate for particle addition is found to be 30-40 gm/min [18]

4 **Melt degassing** – When melt is degassed by the addition of hexachloroethane tablets, there is a reaction between the aluminium alloy and it This results in release of chlorine gas, which completely alters the surface properties and results in loss of recovery [15,19]

CHAPTER 3.

SINGLE ROLL CONTINUOUS STRIP CASTER

In this investigation casting of composite strips directly from the liquid melt has been done using the single roll strip caster designed and fabricated by Mehrotra and coworkers The detailed description of the caster is given elsewhere [15,10,18] Only a brief description of it is presented in this chapter A schematic diagram of the caster showing its various components is presented in Fig 3 1

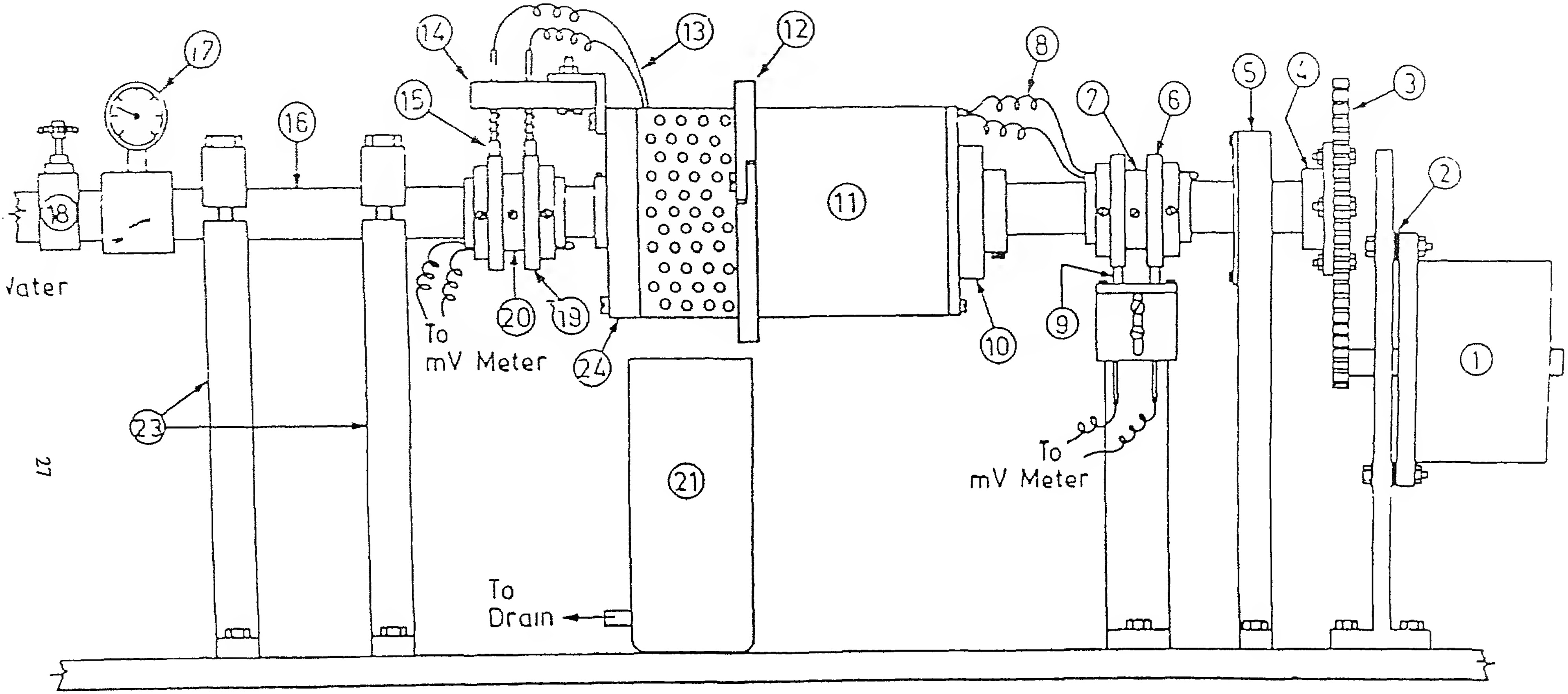
3 1 VARIOUS COMPONENTS OF THE STRIP CASTER

The main components, which combine to form the caster, are as follows

a) Tundish / liquid melt reservoir
b) Caster drum assembly
c) Water cooling system
d) Knife edge
e) Stepper motor
f) Electronic rpm controller device
g) Thermocouple assembly

3 1 1 Tundish / liquid melt reservoir

The tundish, which holds the liquid melt, is made up of fire clay refractory brick It is carved out from cuboid fire clay refractory brick in a specified size and shape The tundish controls the flow of the liquid on the rotating caster drum in a uniform manner by maintaining a constant height of the liquid melt The tundish wall facing the drum has the same concentric profile as that of the caster drum It has a rectangular opening at the bottom that acts as an outlet for the liquid melt



(1) Stepper Motor (2) Rubber Washer (3) Reduction Gear (4) Brass Coupling (5) Ball Bearing Holder
(6) Copper Ring (Rotating) (7) Teflon Sleeve (Rotating) (8) Thermocouple (9) Carbon Brush
(10) Brass Flange (11) Copper Drum (12) Brass Ring (13) Thermocouple (14) Teflon Plate
(15) Carbon Brush (16) S S Tube (17) Pressure Meter (18) Valve (19) Copper Rinn (Stationary)
(20) Teflon Sleeve (Stationary) (21) Water Collector Tank (22) Brass Flange (23) M S Stand
(24) Cover Plate (Brass)

Fig 3 1 Schematic diagram of single roll continuous strip caster assembly

The placing of the tundish is carefully done so that it is very close to the caster drum without touching it to avoid scratching of the drum surface At the same time it is ensured that gap between the drum surface and the tundish is not large enough for the molten metal to leak through it A sketch of the tundish showing its various dimensions is given in Fig 3 2

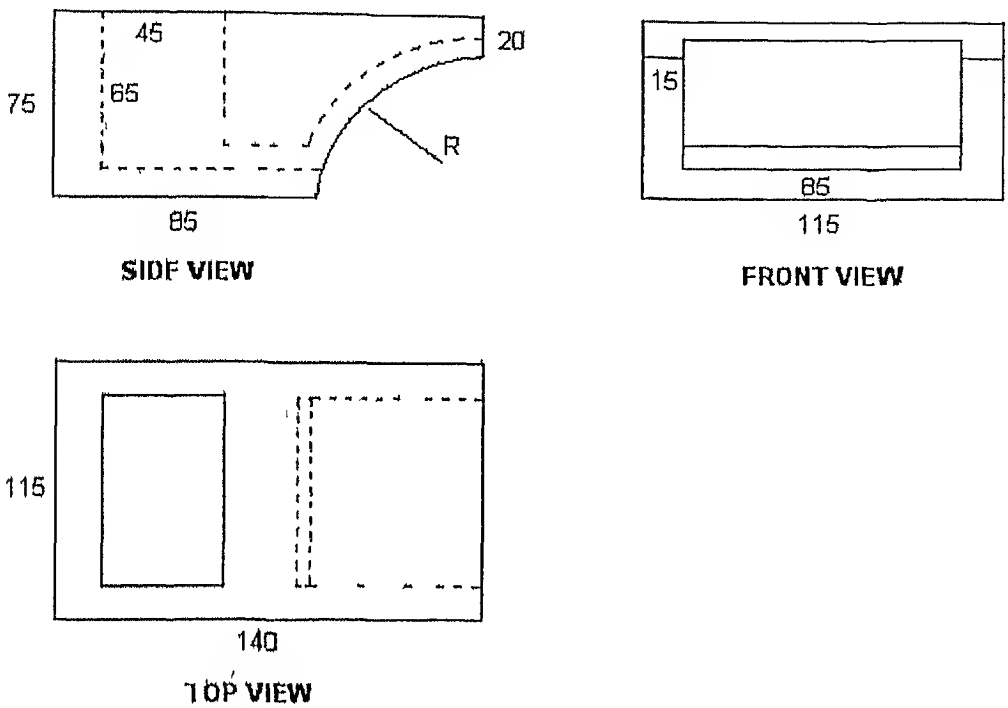


Fig 3 2 Tundish with its various dimensions (in mm)

3.1.2 Caster drum assembly

Caster drum is cylindrical in shape, which is open at both ends It is made up of high purity (99 9%) copper There is an internal cooling arrangement through water sprays The whole length of the caster is divided into two portions One is the caster drum and the other one is water outlet portion, which is drilled with holes on its surface and provides an outlet for cooling water The inner surface of the drum is tapered towards the water exit portion to facilitate the easy

flow of the cooling water Both ends of the drum are fitted with brass flanges One end of the caster drum is connected to the shaft of the electronically controlled stepper motor, which varies the speed of the caster drum between 4 rpm to 50 rpm The other end of the caster drum is connected to a water pipeline, which also holds the water spray assembly inside the drum The caster drum and the water outlet portion of the drum are seated on the outer surface by a brass ring so that the exit water does not come in contact with the molten melt or the solidifying strip The caster drum is also fitted with thermocouples at two points to measure the temperature continuously during the casting process

3 1 3 Water spray system

The main function of this assembly is to continuously cool the inner surface of the rotating caster drum when it comes in contact with the liquid melt This assembly consists of four nozzles placed at right angles to each other and in two rows such that it covers almost entire inner surface area of the caster drum to ensure its uniform cooling The spray nozzles are specially designed such that each nozzle generates a fully developed water cone with a cone angle of about 70° The nozzles are fitted through the manifolds on the horizontal stainless steel pipe that passes through the brass flange on one of the openings of the caster drum This pipe remains stationary when the drum rotates

3.1.4 Knife edge

The main purpose of knife edge is to peel of the solidified strip from the surface of the caster drum This is made of aluminium sheet, which has a sharp edge that peels off the strip from the surface as the caster drum rotates The peeled strip is then moved over the knife edge that acts as platform to rest the solidified strip The position of the knife edge can be correctly positioned through its mount to give required horizontal and vertical movements for uniform peeling of the strip

3.1 5 Stepper motor

A uni-step motor is used to rotate the caster drum at any specified rotational speed It runs with a 12 volt DC supply that is controlled by an electronic device The motor is directly coupled with a caster drum through a connecting shaft or it can be coupled through a gear assembly to obtain wider range of the speed of the caster drum

3 1 6 Electronic rpm controlling device

This electronic device controls the rpm of the stepper motor, which further governs the movement of the caster drum Using this device the rotational speed of the caster drum can be controlled

3 1 7 Thermocouple assembly

To measure the temperature of the caster drum wall at two points during the casting, chromel-alumel thermocouples are used One of the thermocouple is fixed at the midpoint along the length of the casting zone while the second is located almost at the water-cooled surface of the caster drum

3.2 PROCEDURE OF STRIP CASTING ON SINGLE ROLL STRIP CASTER

Casting of strip is done by first preparing the liquid melt and preheating the tundish When the tundish is preheated to a specified temperature the caster is then switched on The rpm of the stepper motor is adjusted such that the caster drum rotates at a speed chosen for the casting A prespecified water flow rate is set for cooling the caster drum Liquid melt is then poured into the tundish, which is already preheated to avoid any thermal shock Pouring of the molten melt is done such that a specified liquid level is maintained in the tundish throughout the casting process A metal pool is formed in the annular space between the rotating caster drum and the tundish wall As soon as the caster drum comes in contact with the molten composite melt, formation of solidified strip on the surface of the

caster drum begins During the initial stage of casting, the first portion of the solidified strip is dragged over the drum surface with the help of a dummy bar, which is a bend aluminium strip of the same width as that of the strip The strip itself gets peeled off from the caster surface by the knife edge when it reaches the top of the drum and travels on its own to the surface of the knife edge, which acts as a platform for holding the solidified strip The strip casting continues as the molten melt is poured into the tundish The hot solidified strip is then cooled in atmosphere, marked and preserved for its evaluation of the mechanical and micro structural properties Figure 3 3 is a schematic diagram showing the working of the caster and formation of the strip

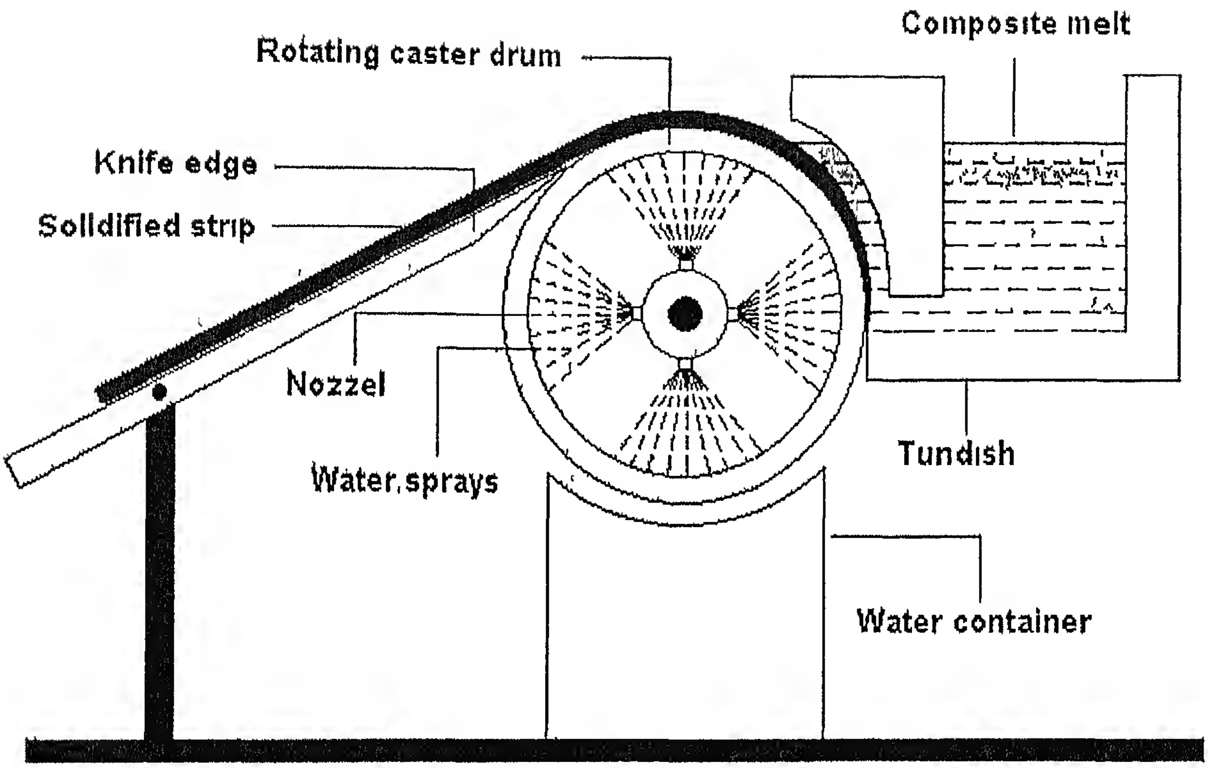


Fig 3 3 Schematic diagram showing the casting process

CHAPTER 4

EXPERIMENTAL PROCEDURE

This chapter deals with the complete description of the experimental procedure that was employed to produce the composite strips It also describes the remedial steps that were taken during the casting process when problems were faced in producing sound castings Preparation of standard specimens for mechanical testing and optical and SEM observations are then presented at the end of this chapter

4 1 MATERIALS USED FOR COMPOSITE MELT PREPARATION

Main material for preparing the aluminium graphite composites is binary alloy of Al-Si as a matrix metal and powdered graphite as a reinforcing element Table 4 1 shows the composition of the commercial Al-Si (LM6) alloy, which was obtained from Bharat Aluminium Company (BALCO) Blocks of the aluminium alloy were cut from the ingots for various experiments

Powdered graphite was obtained by grinding graphite blocks By sieving their powder, size fractions 44 -53 μm (fine) and 53-75 μm(coarse) were obtained

Magnesium cuboids were cut from the block of commercially available pure magnesium casting

Elements	Wt %
Aluminium	84 46
Silicon	15 0
Copper	0 22
Magnesium	0 09
Iron	0 23

Table 4 1 composition of Al- Si alloy

4.2 PREPARATION OF THE COMPOSITE MELT

This is the foremost and crucial step towards production of strips on the caster. The principle of Vortex method was applied to incorporate the graphite particles in the melt of Al-Si alloy. Figure 4.1 shows the schematic diagram of the experimental set up which includes the resistance furnace for heating the melt, the crucible for holding the molten melt and the stirrer for stirring the melt from the top.

Following steps were taken in series to prepare a good homogeneous melt of graphite in Al-Si alloy

- Melting of Al-Si alloy
- Addition of degassing compound
- Addition of magnesium
- Preheating of graphite particles
- Addition of graphite particles in the melt
- Stirring of melt

4.2.1 Melting of aluminium alloy

The aluminium alloy in form of cubical blocks was placed in the crucible and was heated above its melting temperature. The current and the voltage supplied to the furnace were kept high so that the melting temperature could be achieved quickly. This was done because aluminium has a high oxidizing tendency. The charge was then maintained at a prespecified temperature between 720-780^{0}C and the slag and dross floating on the melt surface was skimmed off. The charge was then ready for addition of degassing compound.

4.2.2 Addition of degassing compound

Hexachloroethane tablets were added quickly to the melt and the melt was stirred with the stirrer for a few minutes.

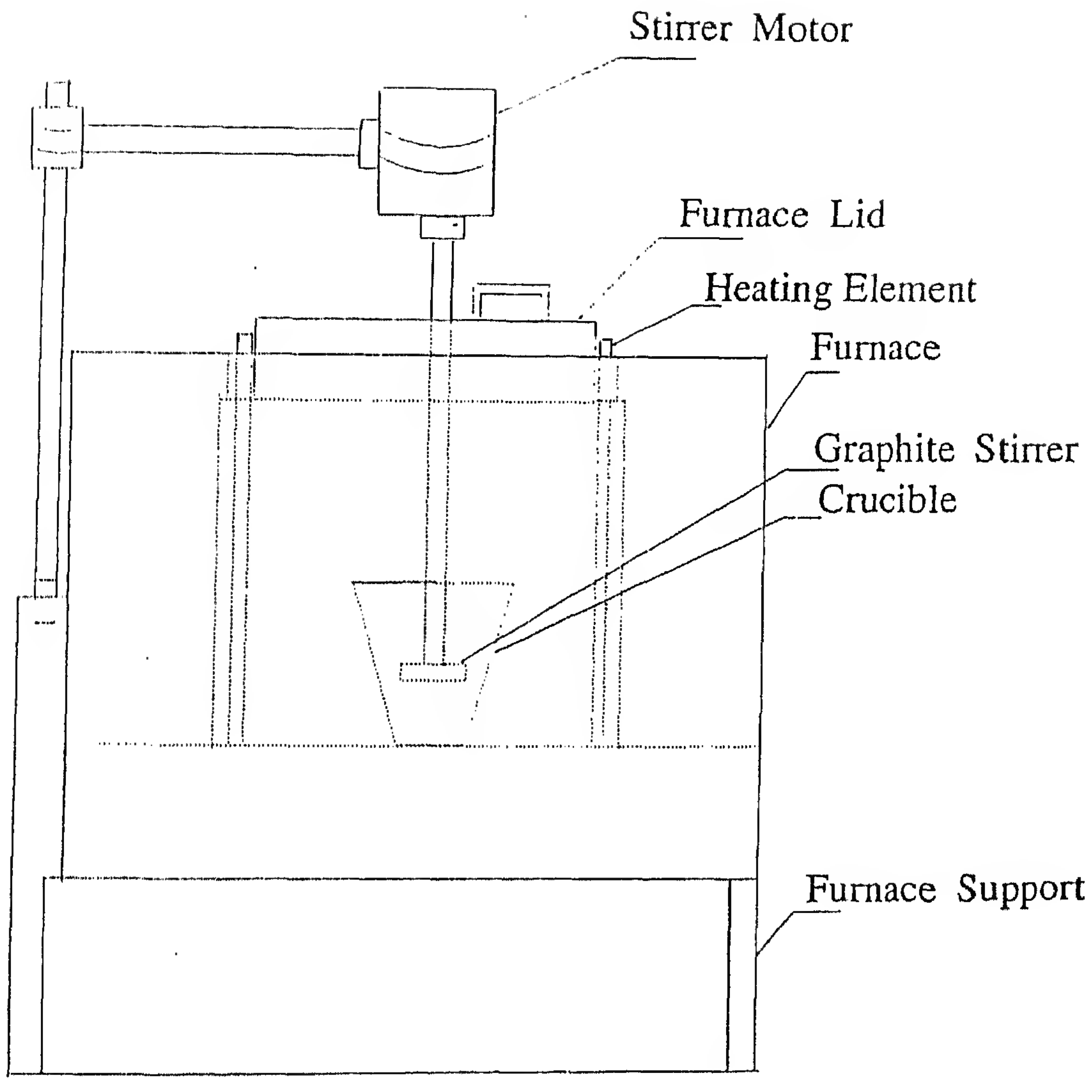


Fig. 4.1 Schematic diagram of the experimental set up

4 2 3 Addition of magnesium

After the addition of degasifier, magnesium cube (1 5-2 5 gm) was tied at one end of a graphite rod with pure aluminium wire and was inserted at the bottom of the melt The rod with attached magnesium was kept in the melt for a few minutes and the melt was slowly stirred manually with this rod until all magnesium got dissolved into the melt Care was taken to minimize heat losses during this whole operation After sometime any slag if present was removed

4 2 4 Preheating of graphite particles

It is necessary to preheat the graphite particles before introducing these into the melt [15] The reasons for this have been explained in some details in chapter 2 Heating of powdered graphite particles was done in a resistance heating furnace at 400^0 C for 1 hour

4.2.5 Addition of graphite particles

After the preheating, addition of graphite particles in the melt was an important and deciding step for preparation of the composite melt The time lag between heating of particles and their insertion in the melt was kept to a minimum Graphite particles were then added into the melt with the help of a long funnel Melt was continuously stirred with the help of the stirrer while the graphite was being added to it The rate of addition of graphite was 30-40 gm/min for uniform mixing and better recovery Care was taken that the particles were being dropped in the zone of vortex that was created by the stirrer The melt temperature was maintained between 720-780^{0}C to avoid rejection of particles

4 2 6 Stirring of melt

After the complete addition of particles, stirring of the melt was continued for about 10-15 minutes at 400-500 rpm The stirrer rod of graphite was preheated in the furnace before inserting into the melt, to avoid thermal shocks and the consequent reduction of the melt temperature

Necessary precautions were taken to ensure that during all these above mentioned steps, temperature of the melt did not fall below its melting temperature All addition and stirring operations were performed through a small opening in the refractory cover of the furnace Temperature of the melt was continuously monitored using a thermocouple Any slag formed during various stages of the operation was removed from time to time

4 3 PROBLEMS ENCOUNTERED DURING MELT PREPARATION AND REMEDIAL MEASURES EMPLOYED

While preparing a composite melt of aluminium-graphite, several technological problems were faced If not taken care of, these problems had adverse effect on the quality of casting, homogeneity of the melt and recovery of the graphite particles This also led to increased inclusion content in the melt as well as loss of matrix metal in the form of slag

The main problem arose because of non-wetting characteristic of graphite particles in the molten aluminium alloy melt So following measures were taken to overcome this problem

- Stirring of particles with a stirrer rod having angular and oriented teeth was chosen to produce uniform vortex
- Stirring of the melt was performed by altering the position of the stirrer rod to the region of graphite particles, which could be seen floating on the surface of the melt
- Magnesium was not used in the form of turning because in this form it has the tendency to catch fire when incorporated in the melt causing severe loss of Mg To avoid this, magnesium was added in the cuboid form
- Temperature was closely monitored Any fall in it was immediately adjusted because low temperature reduces the wetting tendency of graphite particles
- Preheated graphite powders were sprayed to avoid coagulation after heating
- Instead of maintaining the temperature of the melt outside the furnace, it was maintained in the furnace itself before pouring into the tundish This step

ensured that graphite particles did not get enough time to float to the surface of the melt

4.4 OPTIMIZATION OF PROCESS PARAMETERS FOR EXPERIMENTAL INVESTIGATION

For obtaining a sound casting there is a range of values of process parameters that may be employed while using the single roll continuous strip caster A series of experiments were performed and several trials were made to optimize the caster parameters like height of liquid melt in the tundish, tundish nozzle gap cooling water flow rate, pouring temperature, etc Table 4 2 shows the variables of the casting during strip casting process and their ranges Similarly Table 4 3 shows the variables and their ranges for various steps during melt preparation

4 5 EVALUATION OF COMPOSITE STRIPS

Composite strips produced under different operating conditions subjected to evaluation by mechanical testing and microstructural observations

4.5 1 Evaluation by mechanical testing

For mechanical testing of the strips tensile specimen were produced in longitudinal direction Prepared samples match with the dimensions of ASTM standards as shown in Fig 4 2 It was ensured that the samples were flat and there are no surface cracks

Tensile testing was done on INSTRON 1195 tensile testing machine In this test automated load verses displacement plots were recorded on a graph paper and then ultimate tensile strength and percentage elongation measured

Hardness was measured on automatic Rockwell Hardness Tester on scale 'B' Strip samples were uniformly flattened and polished for this test to prevent any surface crack

Process variables	**Range of values**
Speed of caster drum	14-22 rpm
Tundish nozzle gap	10-20 mm
Height of liquid metal	10-40 mm
Pouring temperature	595 - 620 ^{0}C

Table 4 2 optimized value for casting parameters

Preparation steps	**Process variables**	**Range of values**
Amount of particles added	Size	44-75 µm
	Amount	4-10 %
Particle variables	Preheating	400^{0}C for 1 hour
	Rate of particle addition	30-40 g/min
	Temperature of addition	620-680^{0}C
Mg addition	Amount	1 5 – 2 5 wt %
	Temperature of addition	620 – 680^{0}C
Stirring parameters	Rpm of stirring	400-500
	Time of stirring	10-15 minutes

Table 4 3 Optimized value of melt preparation variables

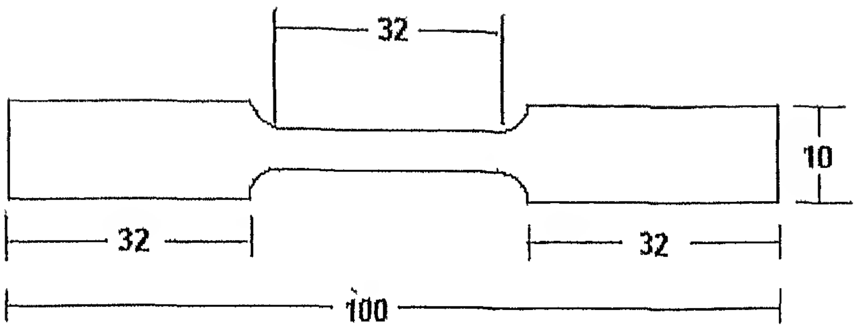


Fig 4 2 Standard ASTM tensile specimen (all dimensions in mm)

4.5 2 Evaluation of microstructure

Five samples of each strip were cut out from the middle of the strips and from both edges to see the distribution of graphite in the matrix of Al-Si alloy

These samples were then mounted by cold setting compounds The grinding and emery paper polishing was done on grade 1/0 to 4/0 papers This was followed by wheel polishing, first with 1 μm and finally with 0 3 μm alumina suspension The alumina suspension was prepared using distilled water The wheel polishing was continued till a mirror surface was obtained Similarly for SEM examination, samples were prepared

Optical microscopic observations were essentially carried out to see the distribution of graphite particles and to calculate the percentage recovery of graphite particles by quantitative metallography

SEM observations were done on JSM 840A machine to see the segregation of silica on the surface of graphite at different magnifications

CHAPTER 5.

RESULTS AND DISCUSSIONS

This chapter deals with the evaluation of composite strips that are produced on the caster As mentioned in chapter 4, several castings were produced by varying operating parameters one at a time Process parameters, which were varied, included the amount of reinforcing particles, size of the reinforcing particles, speed of rotation of the caster drum and the amount of magnesium added Mechanical properties and microstructure of all these strips has been examined and the results and their analysis are presented in this chapter

To ensure reproducibility of the experiments, one set of experiment for casting Al-7wt %graphite (coarse), 18 rpm of caster drum speed, was repeated 6 times and tensile test value obtained for each strip was 124,121,119,116,122 and 118 MPa respectively The average strength of these similar strips was equal to 120 MPa, and the deviation in strength value of these strips was found to be ± 4 MPa This result shows good reproducibility of tensile property for the strips produced by this technique

5 1 EFFECT ON RECOVERY OF PARTICLES IN THE MELT

Recovery is defined as the fraction of particles that actually gets incorporated in the liquid melt when a certain amount of particles is put into the melt During the experiments when graphite particulates were put into the molten aluminium alloy only a fraction of these were retained by the melt and the rest floated on to the melt surface, which was removed along with the slag To increase the recovery of graphite particles magnesium was added into the melt Figures 5 1 and 5 2 show the effect of magnesium addition on percentage recovery of graphite particles of fine (44-53 μm) as well as coarse (53-73 μm) particles for two different initial amounts of graphite particulates - 5wt % and 7wt %, respectively

Recovery of graphite particles was determined using quantitative metallographic calculations It is seen in these figures that graphite recovery is substantially increased with increased amount of magnesium for both coarse and fine

particles of graphite. Therefore for all other sets of experiments 2.5 wt. % Mg was used for better recovery. Increase in recovery of graphite with magnesium addition is attributed to enhanced wetabilty of graphite particles in the molten aluminium alloy (magnesium reduces the contact angle of graphite particles by modifying the surface of the molten aluminium alloy [15]). For fine size particles the recovery is less than that for the coarse particles because the fine particles have the tendency to agglomerate and thus prevent many particles to come in direct contact with the molten alloy. Another possible reason is larger increase in viscosity of the melt as finer particles with large surface area may act as potential nucleating sites for the rapid solidification of the aluminium alloy [10,18,20].

Recovery of graphite particulates is also affected by the amount of degasser that is added. Figure 5.3 shows this effect. Increase in the wt. of addition of degasser (hexachloroethane) reduces the recovery because ejection of chlorine gas alters the wetting behavior of graphite in molten aluminium alloy which results in rejection of dispersed graphite particles [15,19].

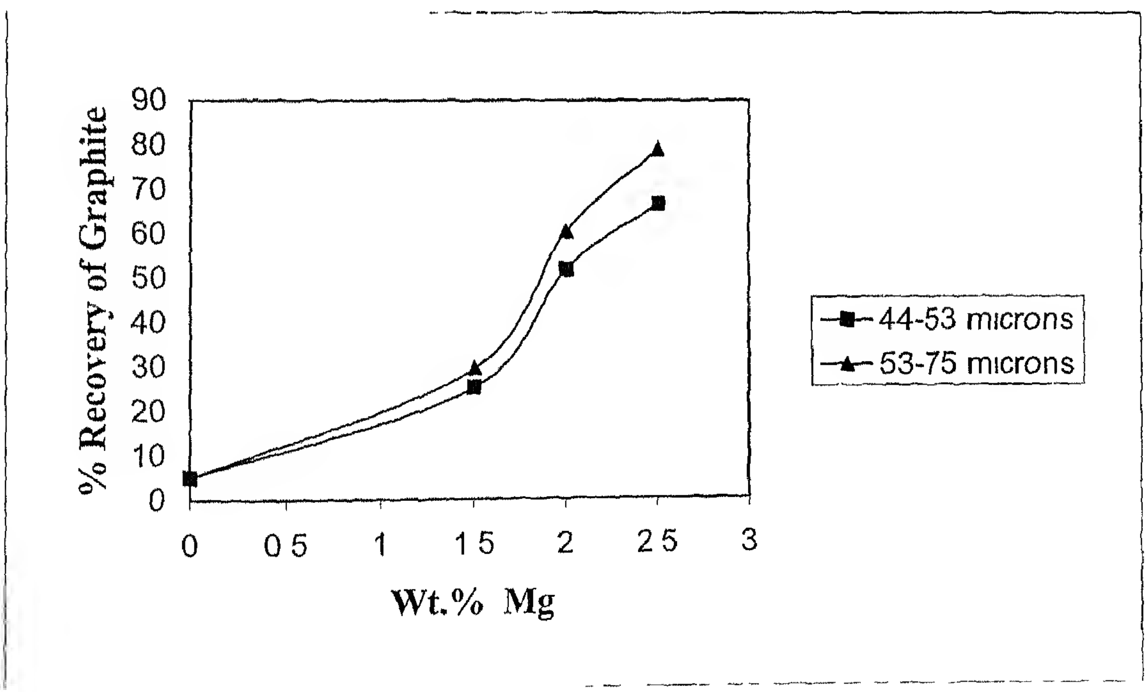


Fig. 5.1 Effect of Mg on recovery (5Wt. % graphite)

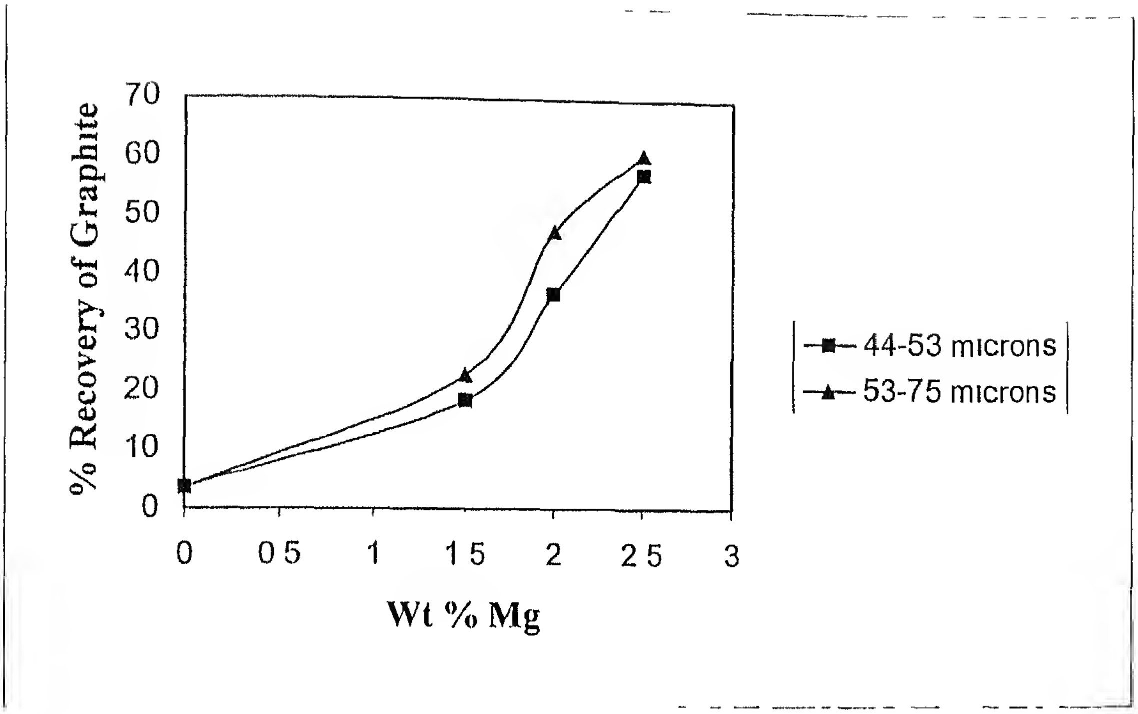


Fig 5 2 Effect of Mg on recovery (7Wt % graphite)

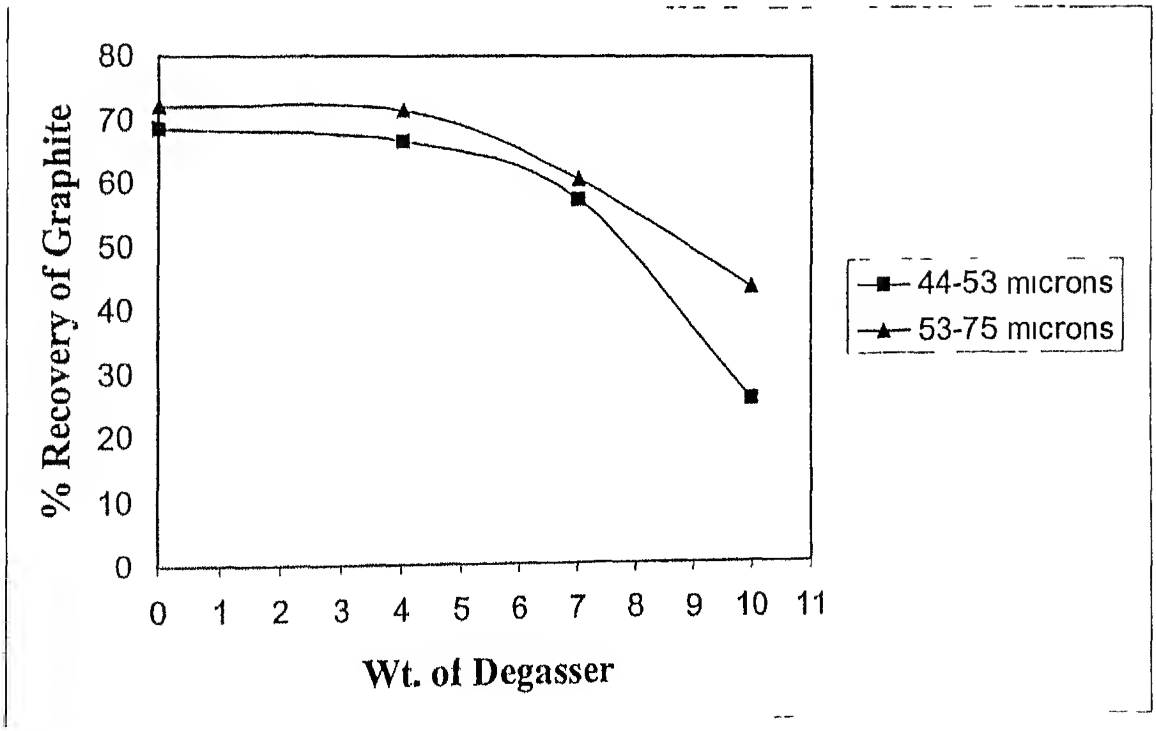


Fig 5 3 Effect of Wt of Degasser (gm) on % Recovery of Graphite

5 2 MECHANICAL PROPERTIES EVALUATION OF CAST STRIPS

Tensile testing and hardness measurement were carried out on cast strips both under as cast and heat-treated conditions The primary purpose of heat treating the strips was to increase the overall strength of the composite as compared to that of the Al-Si alloy matrix because, graphite being a soft and weak reinforcing material, decreases the overall strength of the composite Heat treatment increases the strength and graphite addition enhances the wear resistance of the composite

Effects of amount and size of reinforcement and the effect of speed of rotation of the caster drum on mechanical properties are discussed below

5 2 1 Effect of particle size and amount of graphite added

Results of as-cast and heat-treated strips are as follows In this set of experiments the speed of the caster drum was kept at 18 rpm

5 2 1 1 As cast strips

Graphite particles as reinforcing material in Al-Si alloy matrix result in reduction in overall UTS of the composite [15] Figures 5 4 and 5 5 show the effect of graphite addition on the UTS of the composite strips Figure 5 4 is a plot for the coarse particles while Fig 5 5 is for finer particles Fine particles result in a little higher strength than the coarse particles because the former has larger surface area and gives better bonding between the particles and the matrix, which in turn, helps in load transfer from matrix to the particles Coarser graphite particles may also result in formation of voids in the matrix acting as weaker sites for crack formation and thus decrease the load carrying capacity of the composite [21] Care is to be taken to avoid agglomeration of fine particles otherwise the distribution of the particles will not be uniform and the agglomeration may behave like coarse particles Comparing Fig 5 4 and 5 5, it is seen that the composite with fine graphite particles have good tensile properties with addition of wt % graphite as compared to coarse one, though strength is continuously decreasing with increasing wt % of graphite

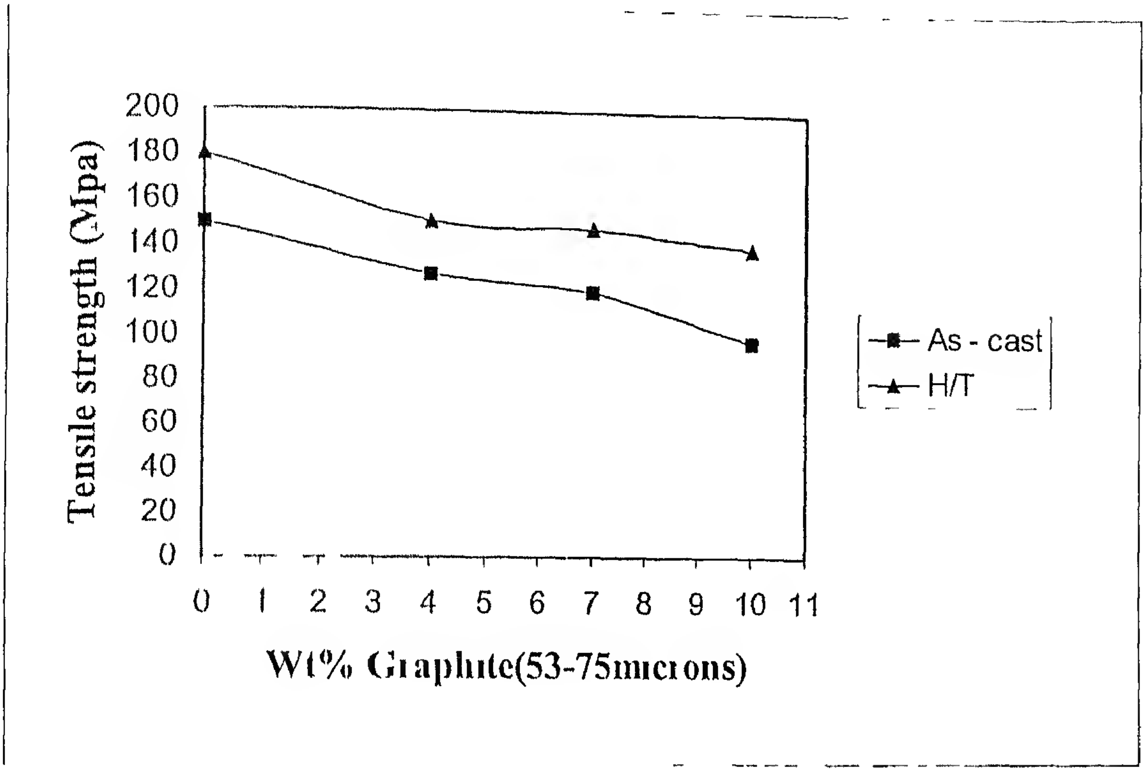


Fig 5 4 Effect on tensile strength of wt % graphite (coarse)

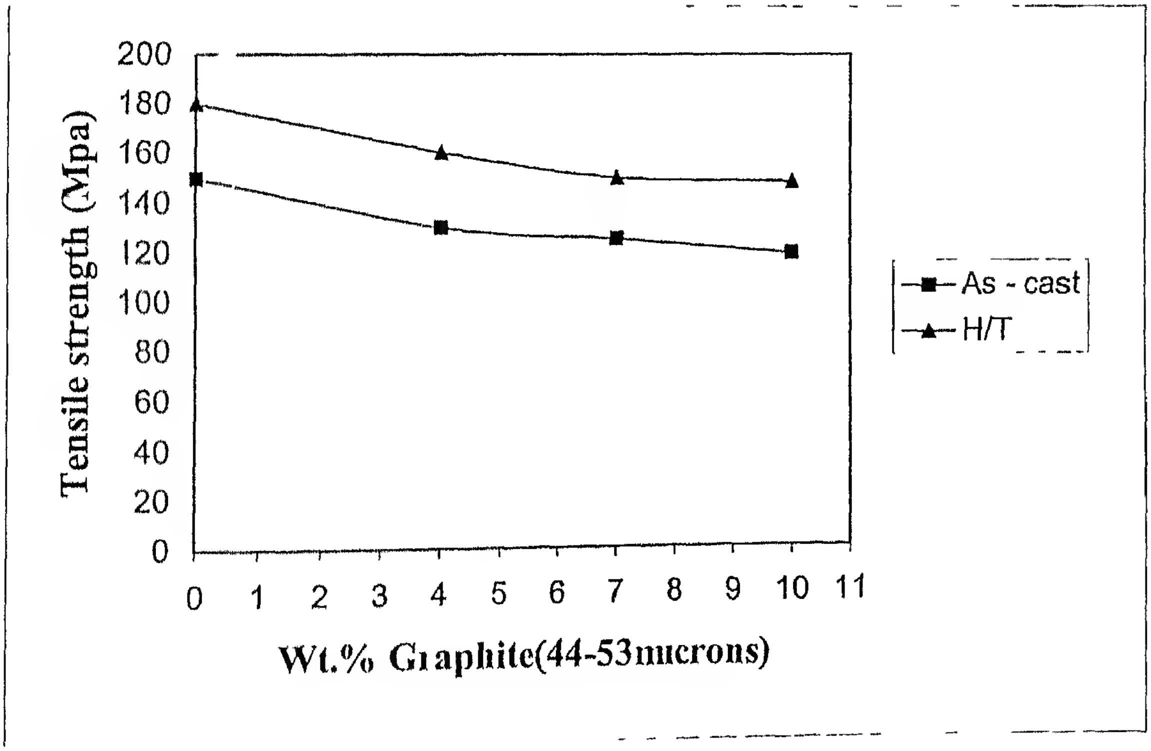


Fig 5 5 Effect on tensile strength of wt % graphite (fine)

Similar trends are also observed for percentage elongation of the composite strips Figure 5 6 and 5 7 show the variation of percented elongation with increase in wt %graphite for both coarse and fine particles Reason for decreasing %elongation is perhaps due to the presence of porosity and the decrease in the mean distance between the reinforcing particles

Figures 5 8 and 5 9 show the trend for hardness (on Rockwell 'B' scale) variations with increased amount of graphite particulates Hardness decreases with increased graphite amount because graphite is softer than the matrix

5 2 1 2 Heat Treated strips

All above figures also show the corresponding tensile strength, % elongation value for the strips heat treated The tensile strength value is always higher for the heat treated strips as compared to the corresponding as cast strips This is attributed to formation of Mg_2Si phase, which is harder and increases the strength of the strip In these figures it is also observed that the strength of heat treated strips is higher than the strength of the pure as-cast matrix of Al-Si

The value of % elongation is less for heat-treated strips as compared to the corresponding as-cast strips

The hardness of heat treated strips is always higher than that of the as cast strips, because of Mg_2Si phase occurring after the heat treatment

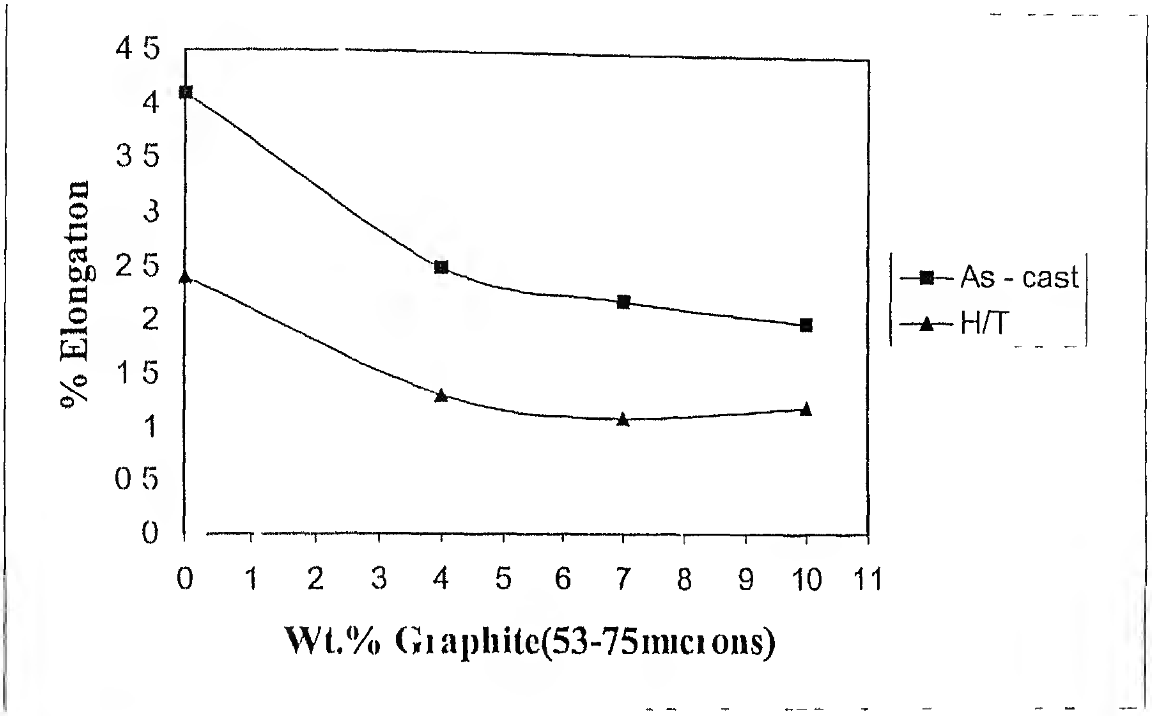


Fig 5 6 Effect on % elongation of wt % graphite (coarse)

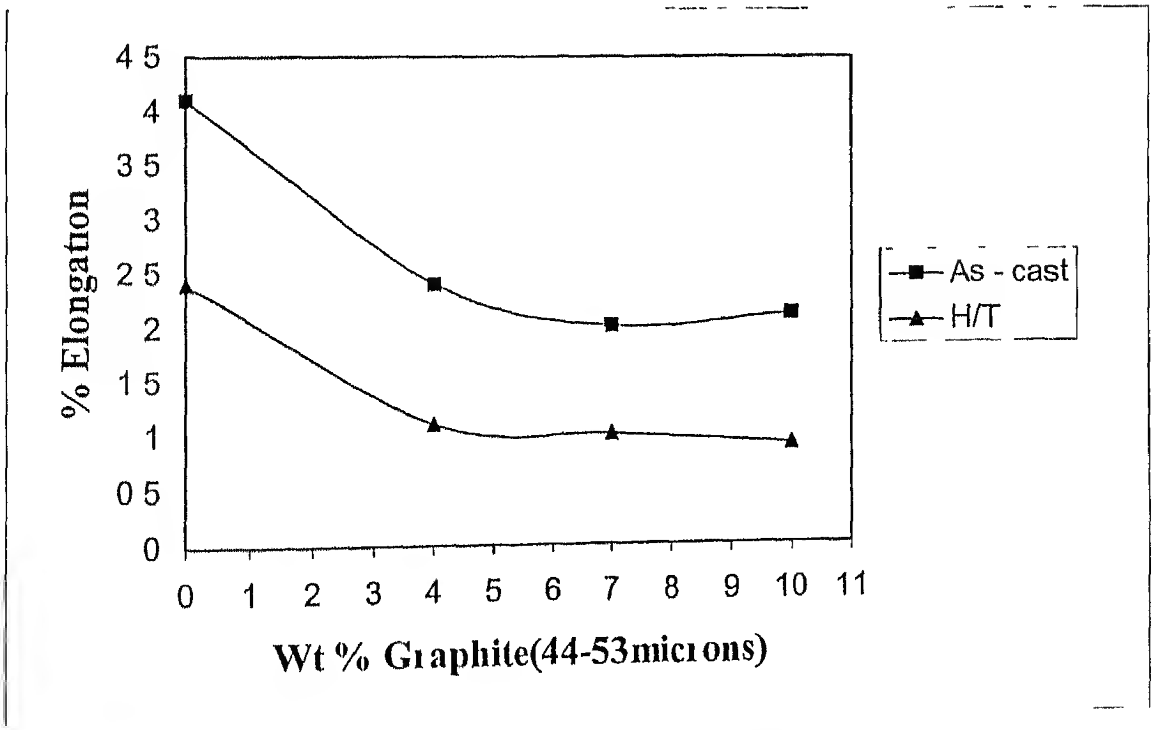


Fig 5 7 Effect on % elongation of wt % graphite (fine)

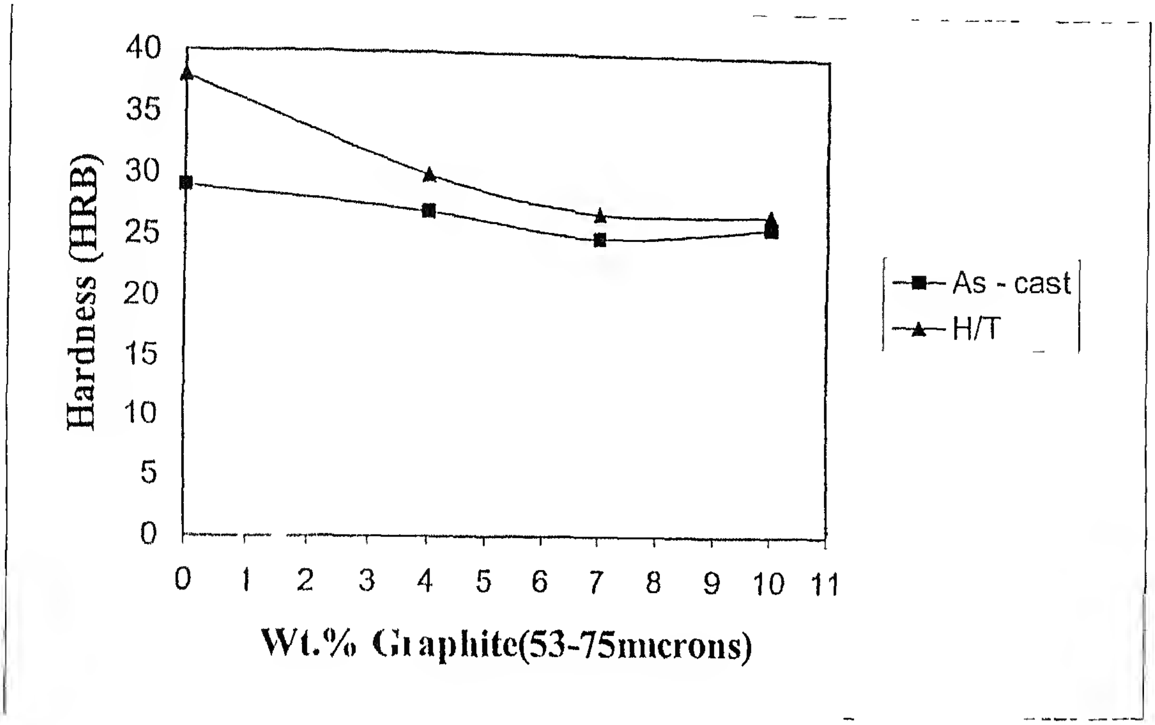


Fig 5 8 Effect on hardness of wt %graphite (coarse)

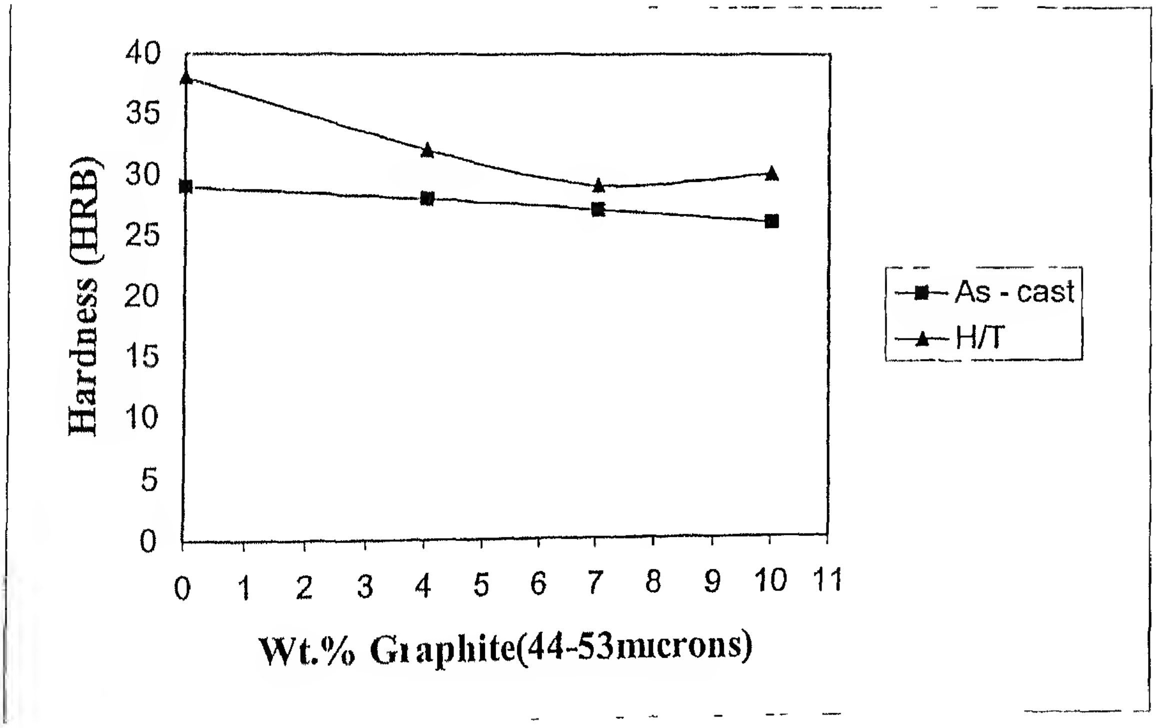


Fig 5.9 Effect on hardness of wt %graphite (fine)

5 2 2 Effect of the RPM of caster drum

Speed of rotation of the caster drum on which solidification of the molten alloy takes place, largely affects the mechanical properties of the composite strips As it also affects the rate of production of strips, its optimization is an important step Figure 5 10 shows the effect of rpm on the tensile strength of the strips Strips for these tests were cast with 7 wt % graphite for both fine as well as coarse graphite It is seen that the UTS of strips having fine graphite particles increases from 114 MPa to 144 MPa, when the rpm is varied from 14 to 22 rpm This trend is in conformity with that observed by Rao [1] The reason for this trend is related to the higher rate of solidification of strips at higher rpm This rate of solidification depends upon the thermal gradient that is present between the surface of the caster surface and the melt This gradient is a function of melt temperature, and the heat transfer coefficient across the melt/drum interface So when the drum rotates, the contact area between the drum and the melt increases linearly with the increase in rpm of the drum and this causes high rate of heat transfer resulting in higher rate of solidification Rapid solidification causes a finer grain structure within the strip, which enhances its strength

Figures 5 11 and 5 12 show the effect of rpm on % elongation and hardness of the strips respectively There is a decrease in the % elongation with increase in rpm of the caster drum One possible reason is that the higher rate of solidification prevents the escape of absorbed gases This absorbed gas causes porosity resulting in decrease in % elongation value Hardness of the strips shows similar trends as that of the tensile strength of the strips because of the small grain size factor

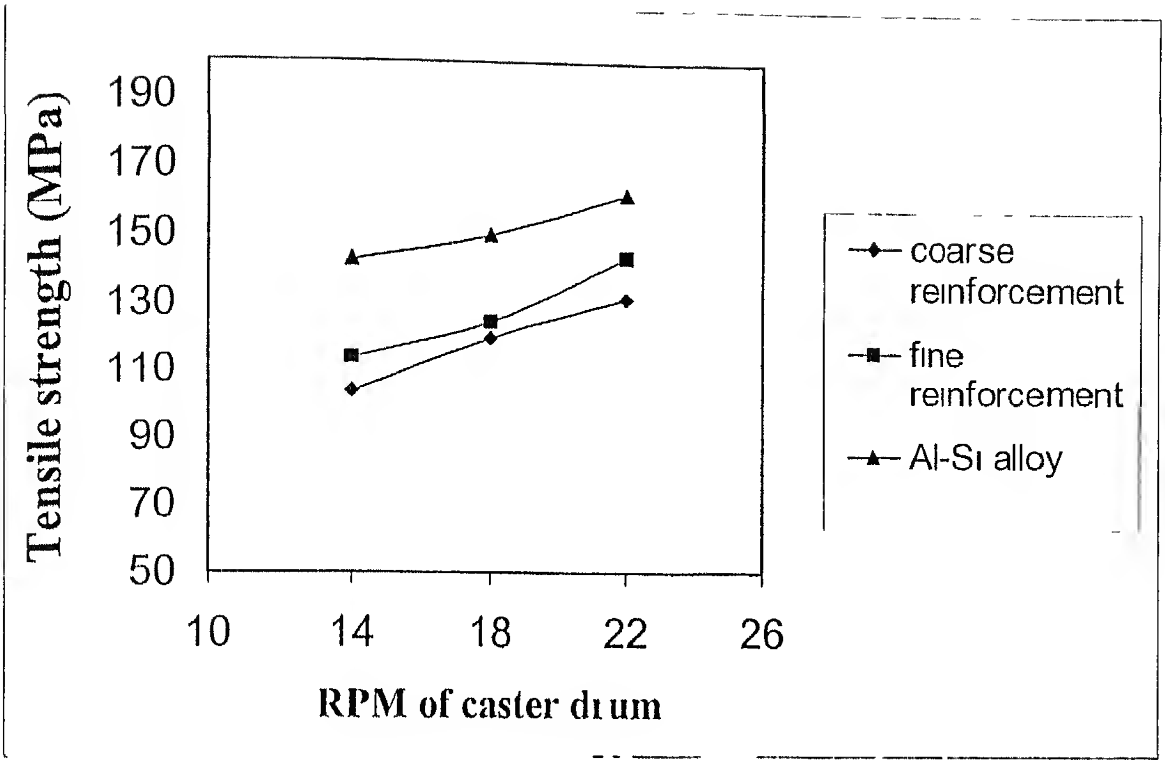


Fig 5 10 Effect of RPM on the tensile strength

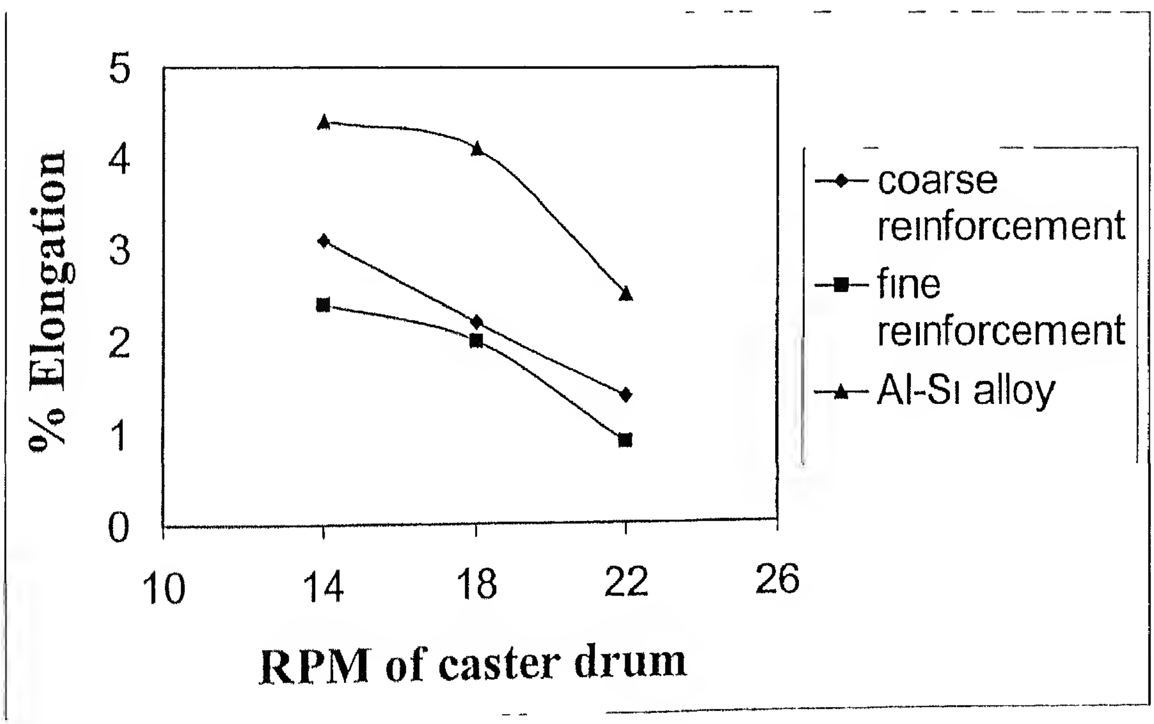


Fig 5 11 Effect of RPM on the % elongation

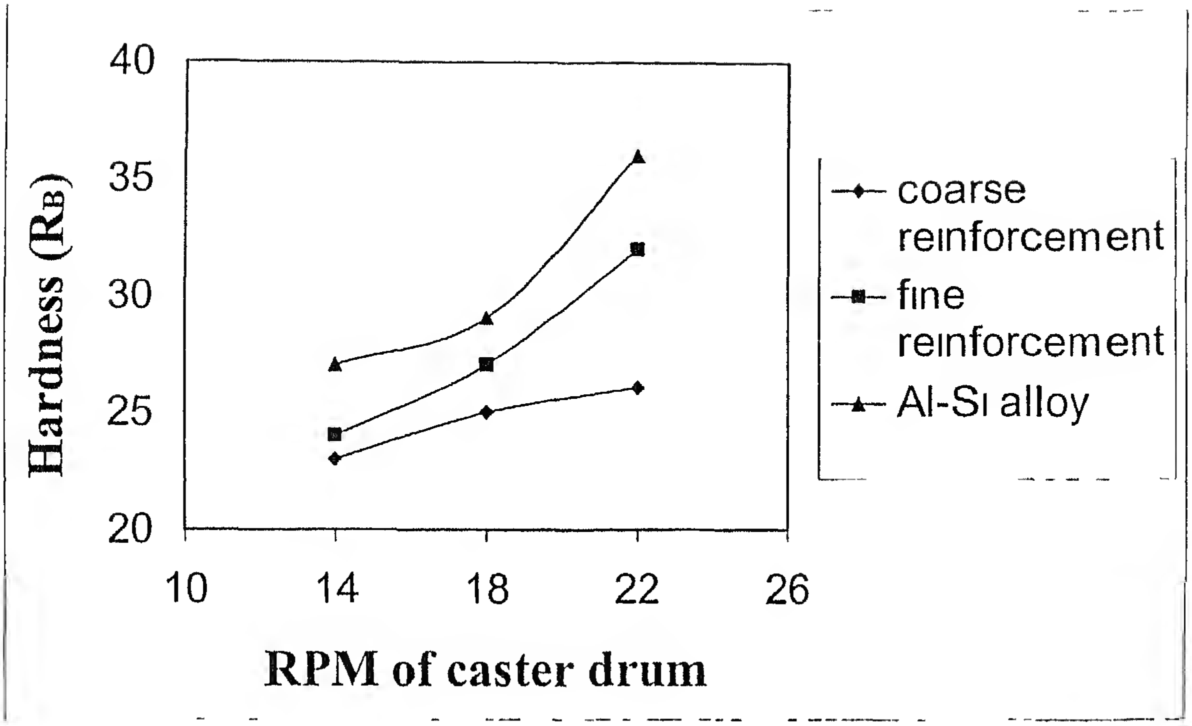


Fig 5 12 Effect of RPM on hardness

5.3 EVALUATION OF MICROSTRUCTURE AND INTERNAL QUALITY

The overall properties of cast strips largely depend on the internal quality i e the amount of porosity, segregation of the particles and inclusions, as well as the surface quality of strips which, in turn, depend on the process parameters like stirring time and melt temperature These effects can be observed by the microstructures of the strips Based on the internal structure and distribution of graphite particles in the melt, the process parameters can be optimized

5 3 1 Distribution of particles in the strips

When graphite particles are put into the melt, only 65 % of the particles are incorporated in the matrix after solidification, and the remaining are lost in handling and slag removal operation This is described in some detail in section 5 1 In this set all experiments were performed with 7 wt % graphite (both coarse and fine) addition in the melt with 2 5 wt % Mg It is seen in Figs 5 13 and 5 14 that fine particles have the tendency to agglomerate in the melt as compared to the coarser ones, when casted at the same rpm This results in homogeneous and uniformly distributed coarse graphite particles in the melt

Distribution of particles is also affected by the rotational speed of the caster drum, which controls the rate of solidification It is seen in Figs 5 14 and 5 15 that at 14 rpm the coarse particles are not as uniformly distributed as at 22 rpm The reason for this difference in behavior comes from the fact that at high rpm graphite particles do not get sufficient time to come up on to the melt surface and coagulate High rpm also increases the vortex and thus results in enhanced mixing in the melt pool region near the drum surface Also care is to be taken that the porosity of the strip is not increased because higher rpm also reduces the time available for absorbed gases in the melt to escape

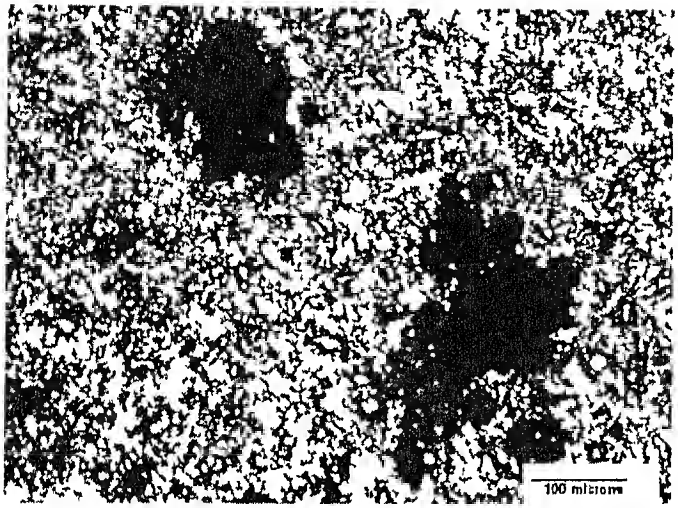


Fig 5 13 Micrograph of Al-Si-7wt %graphite (fine), drum speed 22 RPM, 200X

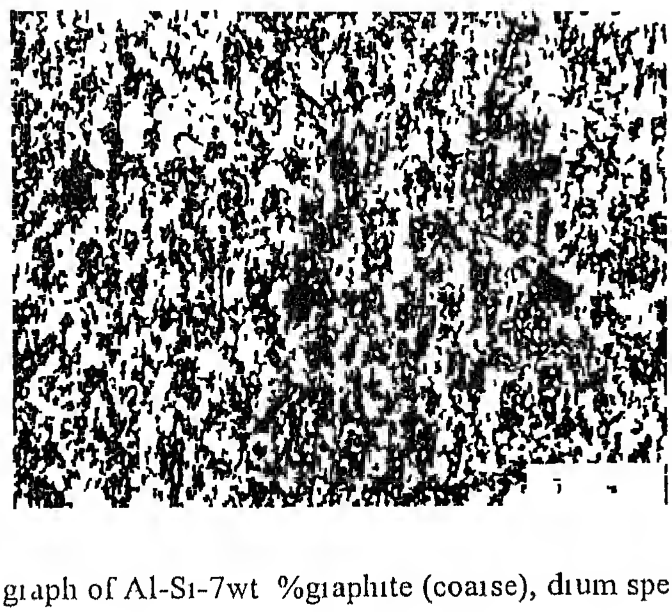


Fig 5 14 Micrograph of Al-Si-7wt %graphite (coarse), drum speed 22 RPM, 200X

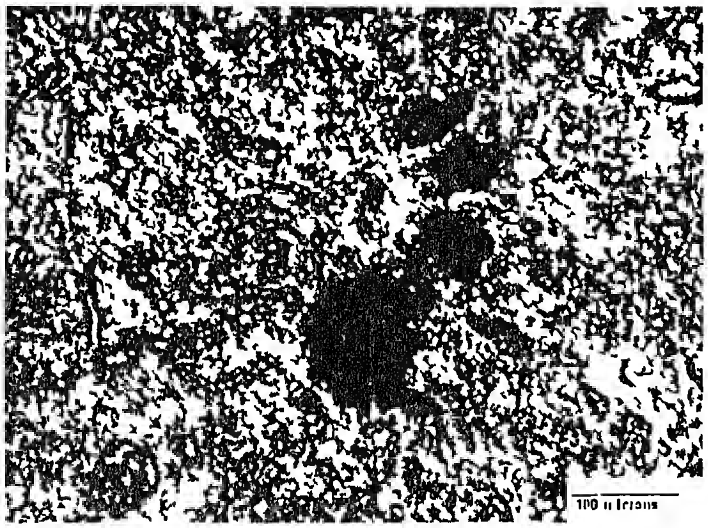


Fig 5 15 Micrograph of Al-Si-7wt %graphite (coarse), drum speed 14 RPM, 200X

5 3 2 Effect of process varıables on strıp qualıty

Process vaııables lıke RPM oí melt stırrer, stırrıng tıme, melt temperaturc, rotatıonal speed of caster drum ınfluence the oveıall strıp qualıty so an attempt ıs made to suggest an ‘optımum value’ for each of these varıables

5 3 2 1 Effect of ıntensıty of stırrıng and stırrıng tıme

Intensıty of stırrıng of melt ıs one of the ımportant parameters whıch control the qualıty of the cast strıps ı e good surface, unıform dıstrıbutıon of partıcles and also thc recovery of gıaphıte partıcles Hıgh ıntensıty of melt stırrıng and longer duratıon of stırrıng results ın more unıform mıxıng of partıcles and ıncreased recovery of graphıte partıcles, by ımprovıng the wettıng characterıstıcs [16] Major deleterıous effect of hıgh speed and longer stırrıng tıme ıs the ıncreased absorptıon of gases ın the melt, whıch adversely affects the strength of the composıte strıps Fıgures 5 16 and 5 17 show the effect of stırrıng tıme and Fıgs 5 17 and 5 18 show the effect of ıntensıty of stırrıng, on the dıstrıbutıon of graphıte partıcles From a large numbeıs of experıments, ıt ıs suggested that 400-500 rpm of stırrıng and 10-15 mınutes of stıırıng tıme are optımum

5 3 2 2 Effect of partıcle sıze

Whıle Fıgs 5 14 and 5 19 show the unıform dıstrıbutıon of coarse partıcles, Fıgs 5 13 and 5 20 show the clusterıng of fıne graphıte partıcles to form a patch lıke stıuctuıc All these samples were taken fıom the mıddle sectıon of the cast strıps to avoıd cnds effects

5 3 2 3 Effect of speed of ıotatıon of the caster drum

Fıguıes 5 14 and 5 15 clearly show the effect of RPM for coarse graphıte paıtıcles It ıs obscıved that agglomeratıon ıs not pıedomınant at 22 rpm and the gıaphıtc paıtıclcs aıe equally spaced So a ıotatıonal speed of 22 rpm was taken to be oí thc optımum value foı havıng a good qualıty strıp

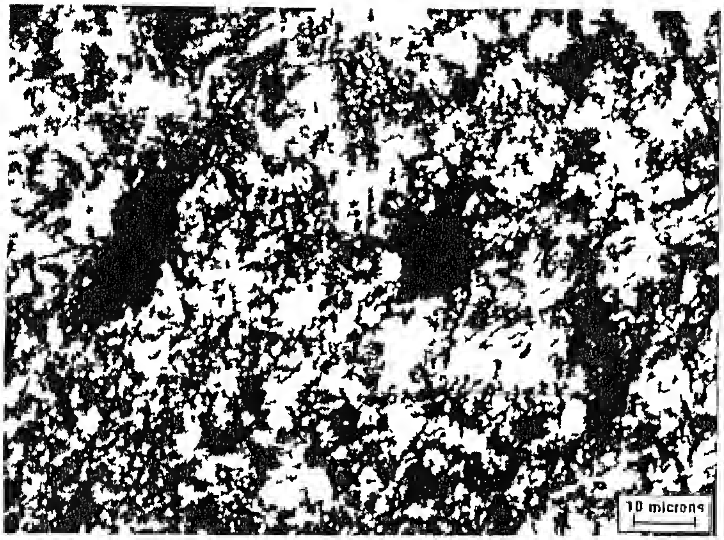


Fig 5 16 Micrograph of Al-Si-7wt % graphite (coarse), stirring for 15 min at 250rpm of stirring speed, 400X

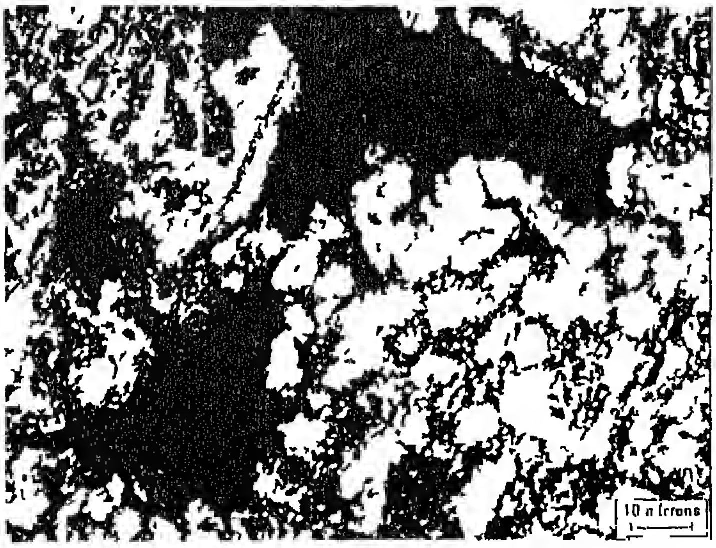


Fig 5 17 Micrograph of Al-Si-7wt % graphite (coarse), stirring for 5 min at 250rpm of stirring speed, 400X

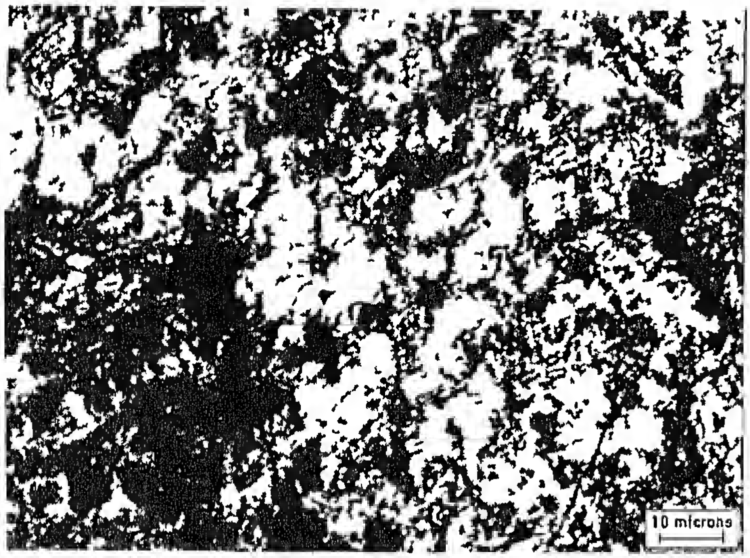


Fig 5 18 Micrograph of Al-Si-7wt % graphite (coarse), stirring for 5 min at 550rpm of stirring speed, 400X

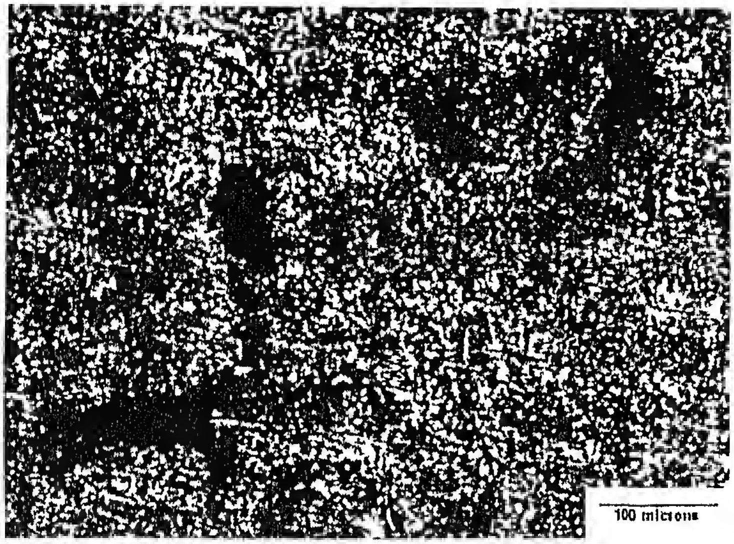


Fig 5 19 Micrograph of Al-Si-7wt % graphite (coarse), caster drum speed of 18 rpm, 200X

Fig 5 20 Micrograph of Al-Si-7wt % graphite (fine), caster drum speed of 18rpm, 200X

5 3 2 4 Effect of melt temperature

High melt temperature has a positive effect on the wetability of graphite particles, but at the same time it has the drawbacks of adsorbed gases in it High temperature also reduces the life of the tundish, stirring rod, graphite stirrer blade, and causes the erosion of refractory particles, which appear in the melt as inclusions Since binary alloy of Al-Si with 2 5 wt % Mg has the melting point of 620^{0}C, sufficient time was given to bring down the melt temperature to this value Care was taken to ensure that the graphite particles did not start floating on the surface of the melt as it has lower density This was achieved by manually stirring the melt in the crucible

5 3.4 Surface quality of strips

From the visual inspection of the top and bottom surfaces of the strips, it was evident that the roll side surface was plane and smooth as compared to the free surface Rao [1] has also reported the similar observations Surface finish of the thicker strips, which were cast at lower rpms of the caster drum, e g 12 to 14 rpm was inferior to thinner strips, which were cast at high rpms Roughness is also related to the intensity of stirring and stirring time prior to casting because increase in both results in increased amount of absorbed gases

5 3 5 Segregation during solidification

When the composite melt of Al-Si-graphite starts solidifying, Si being an alloying element preferentially starts solidifying at the surface of the graphite particles It nucleates and grows on its surface [22,23] This hinders the direct contact of graphite and aluminium Graphite particles get entrapped into the last freezing interdendritic zone of Al-Si alloy Figures 5 21 and 5 22 show the segregation of silicon after solidification on the surface of graphite at 100X and 2500X magnification Silicon solidification should be uniform in the matrix as its presence reduces the unwanted interfacial reaction between graphite and aluminium (formation of Al_4C_3) [24] For having the uniform distribution of solidifying silicon,

the rate of solidification should be high, which can be achieved at high RPM of the caster drum

5 4 WEAR TEST OF GRAPHITE STRIPS

A few wear tests were also conducted on strips that were cast under different experimental conditions on "Wear and Friction Monitor, TR-20, Ducon, Banglore" Figure 5 23 is plot between amounts of wear that has occurred in different Al-graphite composite strips with the passage of time The load applied was about 5 kg, track radius was 45 mm and the rpm of the steel disc was about 212 rpm to have a linear velocity of about 1m/s It is seen in the plot that the composite strips which have more graphite in them, undergo lesser wear for the same time period

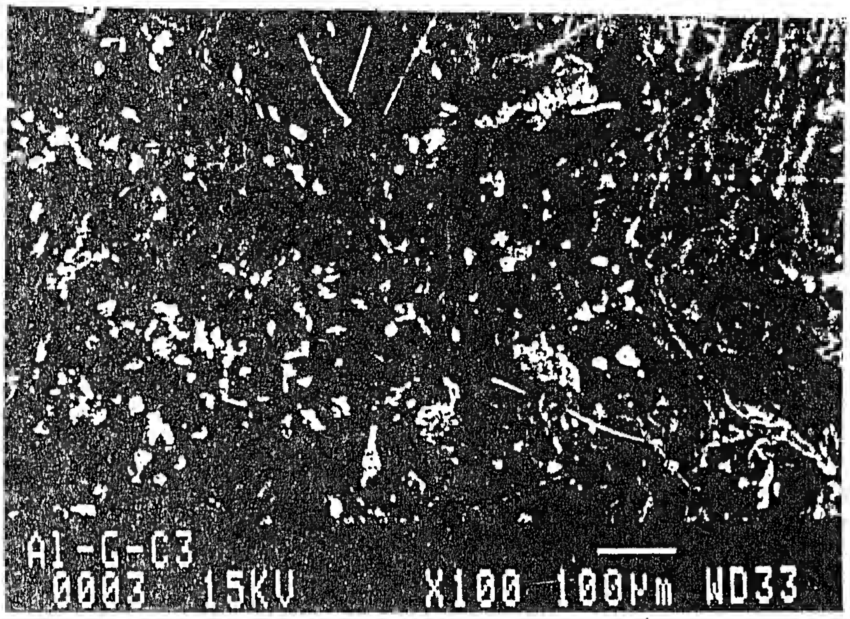


Fig. 5.21 Micrograph of Al-Si graphite showing segregation of silicon, 100X

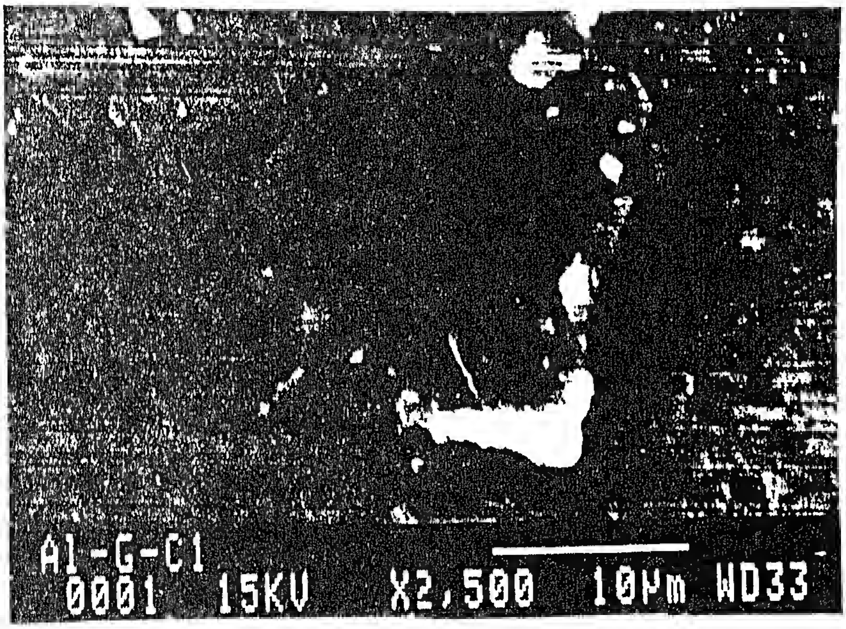


Fig. 5.22 Micrograph of Al-Si graphite showing nucleation of silicon at graphite surface, 2500X

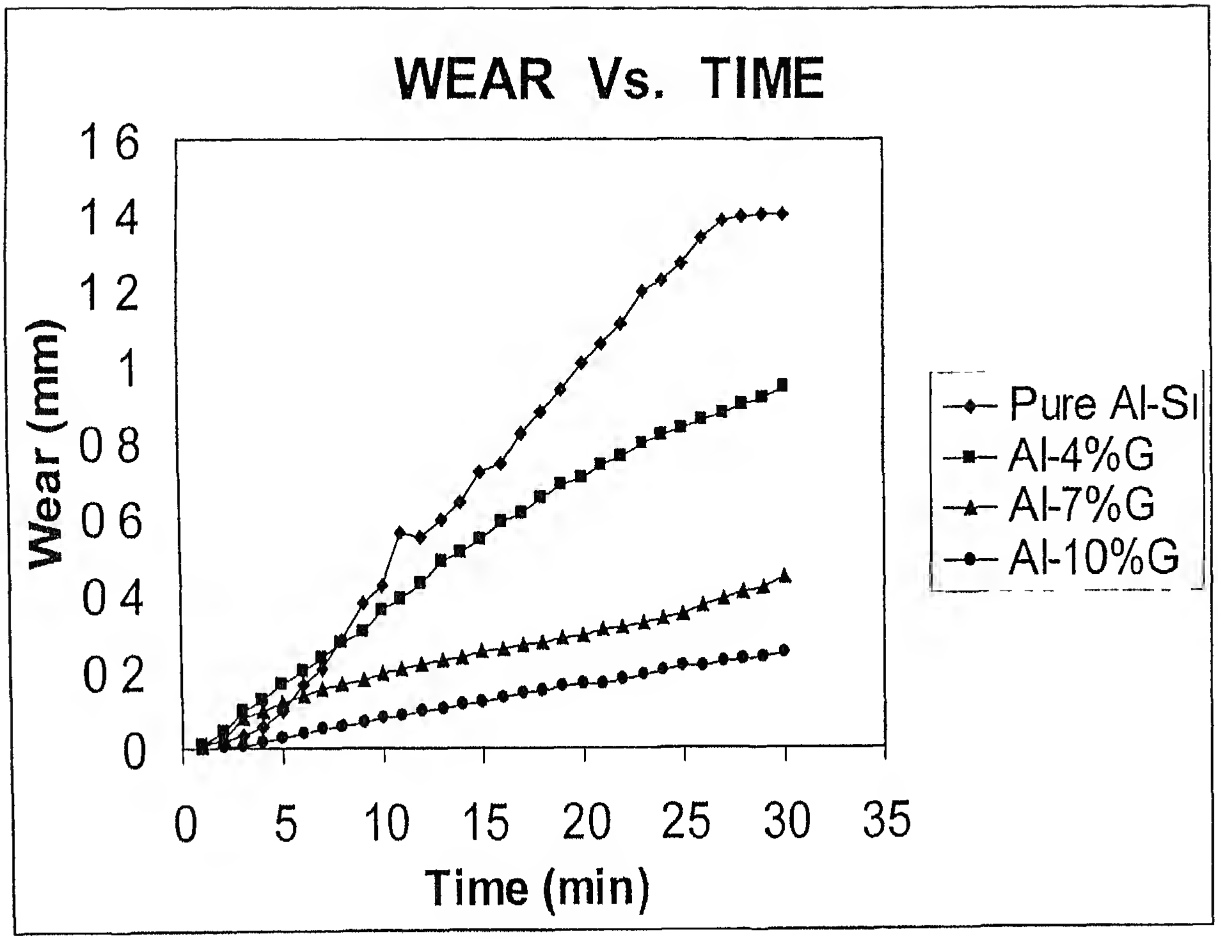


Fig 5 23 Amount of wear in the composite strip with time

CHAPTER 6.

SUMMARY AND CONCLUSIONS

The present investigation can be divided into two parts In the first stage composite strips of aluminium alloy reinforced with graphite, have been produced using single roll continuous strip caster It is designed and fabricated in the laboratory by Mehrotra and coworkers for producing near shape metal strips The main objective of this part of the investigation was to establish the feasibility of producing aluminium graphite composites strips on that caster and to optimize the process parameters Production of strips involved melt preparation during which melt was alloyed with magnesium and preheating of particles was done to improve the wetting property of graphite Vortex method of preparing the melt was employed and continuous stirring of the melt was done to further improve the wetting and homogeneity of the particles in the melt

In the second part the microstructure and mechanical properties of these strips were evaluated Mechanical testing was done by examining the ultimate tensile strength, %elongation and hardness of strips in both as-cast and heat-treated conditions Various effects of process parameters like amount and size of graphite particulates, speed of rotation of the caster drum temperature etc were also examined Microstructural investigations were based on optical and scanning electron microscopy to study the distribution of particles in the strip and to calculate the recovery of graphite particles

Several experiments were performed to analyze the effects of various process parameters and to find optimal value of each of these to produce good quality strips Based on these observations following conclusions are drawn

- It is possible to produce aluminium alloy- graphite particulate MMC strips by using vortex method combined with single roll continuous strip caster
- Strips of different composition can be fabricated by varying the process parameters
- Preheating of graphite particles before mixing into the melt helps in obtaining better recovery

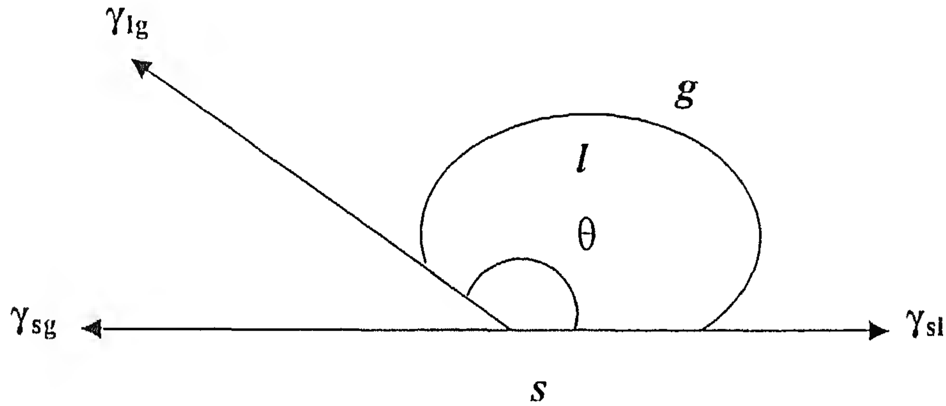
- Addition of certain alloying elements such as magnesium helps in improving the wetting characteristics of graphite
- It is not possible to incorporate graphite particles of size less than 44 μm into the melt
- Increase in degasser compound in the melt substantially reduces drastically the recovery of graphite particles
- Fine particles show better strength than coarse particles if cast with the same rotational speed of the caster drum
- Coarse particles have better recovery than fine particles
- Strength of the composite strips decreases with the increases in graphite content
- Addition of magnesium makes the alloy heat treatable and heat treatment increases the overall strength of the composite It may even be more than the strength of the Al-Si alloy matrix
- Higher rpm of caster drum shows better distribution of graphite particles
- Strength of composite strip is also higher for strips cast at higher rpm
- Segregation of silicon and its nucleation is observed at the surface of graphite particles
- The roll side surface of the strip is smooth while the top side surface exhibits roughness
- Strength of composite strips produced by this technique is comparable with those produced using the conventional techniques of producing aluminium graphite composites
- Ductility decreases while hardness of the strips increases by heat treatment of strips
- Wear properties of composite sheets shows better results with increasing content of graphite

APPENDIX

Physio-chemistry of wetting

The wettability of a solid by liquid melt is indicated by the contact angle θ this angle is correlated to the three surface energy γ_{sg}, γ_{lg} γ_{sl} of solid-gas, liquid-gas and solid-liquid interfaces as shown below in the figure respectively through the well known Young's equation

$$\gamma_{lg} \cos 0 = \gamma_{sg} - \gamma_{sl}$$



For the wetting to take place, the necessary condition is

$$\cos 0 > 0 \quad \text{i e} \quad 0 < 90^0$$

From this condition it is inferred that lower the angle of contact, better is the wetting In other words $\gamma_{sg} > \gamma_{sl}$ The driving force Fw, for wetting can be defined as

Fw = γ_{sg} - γ_{sl} In the extreme case when Fw >= γ_{lg} , θ = 0^0 the liquid spreads spontaneously on the solid For contact angle $0 > 90^0$, the capillary effect requires an external pressure in order that the liquid wets the solid in contact with it However, the application of pressure does not always completely solve the problem, since shrinkage during the solidification may be large enough to cause debonding or void formation

REFERENCES

[1] S P Mehrotra, G Srinivasa Rao and S P Gupta, Evaluation of properties of strips produced using laboratory SRCSC Trans IIM, 52 (1999), 5, 313

[2] Rohatgi P K, Cast metal matrix composites In ASM metals handbook, vol 15, ed 9, Metal park Ohio, p 840

[3] Rohatgi P K, Metal Matrix Composites, Defense science journal, 43 (1993), 323-349

[4] Lesuie D R, Syn C K, Sherby O D, International materials Review, 41(1996), 5, 169-197

[5] Alman D E, Metallurgical and Mineral Transactions Vol 26 A 1995 pp 589-599

[6] Merchant H D, Tyler D E, Chia E H, Rapid quenching strip casting process, Source – Proce of Symp On continuous casting of NF metals and alloys, Chicago, Illinois, sep – 28-29 1988 (ed) TMS pp 67

[7] Haour G, Al- based strips and wires produced by melt dragging technique, source – proc of symp on continuous casting of small cross section,

[8] Vangala P Smitch D, Influence of casting gauge on Hunter roll casting process source- Proc of melt spinning and strip casting research and implementation symp San Deigo , March 1-5 1992 Eric F Mattheys, ed TMS pp 225

[9] Gupta R K, Evaluation and optimization of MMC strips produced by single roll continuous strip caster M tech Thesis, Dept of Mat and Met Engg IIT Kanpur 2000

[10] F Dalannay, L Froyen, A Deruyttere, Review The wetting of solids by molten metals and its relation to the preparation MMC, Journal of Material Science, 22 (1987) 1-16

[11] B C Pai, Copper coating of graphite particles, Material Science and Engg, 21 (1975) 161-167

[12] Umaranikar M H, Production of MMC strips using SRCSC technology M Tech thesis Dept of Mat and Met Engg IIT Kanpur 1998

[13] D M Goddard, Interface reaction during preparation of Al-matrix composites by the sodium process, Journal of Material Science 13 (1978) 1841- 1848

[14] M K Surrapa, Production of aluminium graphite composites using copper coated graphite particles, Metals Technology oct 1978 358-361

[15] Krishnan B P, Surrapa M K, Rohatgi P K, The UPAL process a direct method of preparing cast aluminium alloy graphite composites, Journal of Material Science, 16 (1981) 1209-1216

[16] N Eustathopoulous, I C Toud, P Uesre, The wetting of carbon by aluminium alloys, Journal of Material Science, 9(1974), 1233-1242

[17] Hideo Ohtsu, Al-alloy matrix composites using particle dispersion source (Proc of fifth annual ASM/ESD Advanced comp Conf on design and manufacturing of advanced comp) Dearbon, Michigan Sep 25-28 1989 ASM Int Metal Park Ohio pub Pg 187-199

[18] M K Surappa, P K Rohatgi, Preparation and Properties of Cast aluminium ceramic particle composite, Journal of Material Science, 16 (1981) 983 – 993

[19] Deonath R T, Bhat and P K Rohatgi, Preparation of cast aluminium alloy-mica particle composites, Journal of Material Science, 15 (1980) 1241

[20] P R Gibson, A J Clegg, A A Das, Production and evaluation of squeeze-cast graphitic Al-Si alloys, Materials Science and Technology, July 1985 Vol 1 559

[21] Korsunsky A M and Withers P J, Residual stress effects on fatigue and fracture of MMCs, source (proc of third int conf on comp eggs) New Orleans, La, July 21-26 1996, David hui (Ed) pp459

[22] Rohatgi P K, Interfaces in cast MMCs, Material Science and Engg A162 (1993) 163-174

[23] Krishnan and Rohatgi, Modification of Al-Si alloy melt containing graphite particle dispersions– Metals Tech 11(1984), 41-44

[24] Influence of third element on the interface reaction in MMC Al-Graphite system, Material Science and Engg A-281, issue 1-2, 15 April 2000, pg 239-247

[25] Veronique J M, Liquid state processing Source (fundamentals of MMC) Eds Butterworth – Heinemann Pub 1993 pp3

[26] S K Rhee, J American Cer Society 54, (1971) 376